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DEVELOPMENT OF A BRIDGE SMOOTHNESS SPECIFICATION FOR ILLINOIS DOT

by

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A report of the findings of
Enhancements to Illinois Pavement Management

Project IHR - R24
Illinois Cooperative Highway Research Program

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15. Supplementary Notes

This interim report contains some preliminary specification material. This material is presented only for discussion, and as part of the documentation of the on going research effort by IDOT to develop a comprehensive smoothness specification. Nothing in this interim report should be interpreted as recommending any specification at the present time, and the preliminary specification should not be used or applied to field construction at present.

16. Abstract

Smoothness is considered to be the most important ride quality by the highway user. Although bridges are much rougher than pavements, most of the studies conducted to improve pavement smoothness have been focused solely on pavements. This report describes the effort of the University of Illinois to develop a preliminary bridge smoothness specification for the Illinois Department of Transportation (IDOT). The preliminary specification presented in this research report is based on the testing and analysis conducted under this study and reflects the views and experience of the authors. It is emphasized that this draft specification is not intended for use in construction without significant additional development and field testing. The most suitable index and equipment are recommended based on a literature review of smoothness indices and different pieces of equipment.

In addition, International Roughness Index (IRI) and Profile Index (PI) values were computed from testing 20 recently constructed or rehabilitated IDOT bridges in Illinois using a lightweight profilometer. These data were analyzed in order to set up smoothness limits for bridges, and a correlation between IRI and PI was established.

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TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF ACRONYMS

ARRB - Australian Road Research Board

DOT - Department of Transportation

FHWA - Federal Highway Administration

GDOT - Georgia Department of Transportation

IDOT - Illinois Department of Transportation

IRI - International Roughness Index

IRRE - International Road Roughness Experiment

LTPP - Long Term Pavement Performance

MPR - Mean Panel Rating

MRM - Mays Ride Meter

MRN - Mays Ride Number

MTO - Ministry of Transportation of Ontario (MTO)

NCHRP - National Cooperative Highway Research Program

Penn DOT – Pennsylvania Department of Transportation

PI - Profile Index

QI - Quarter-car index

RARS - Reference Average Rectified Slope

RMSVA - Root Mean Square Vertical Acceleration

RN - Ride Number

RQI - Ride Quality Index

RTRRM - Response-Type Road Roughness Measuring

US - United States

UMTRI - University of Michigan Transportation Research Institute

DEVELOPMENT OF A BRIDGE SMOOTHNESS SPECIFICATION FOR ILLINOIS DEPARTMENT OF TRANSPORTATION

1. INTRODUCTION

Highway users consider smoothness to be the most important pavement quality. Several studies have been conducted to determine the best smoothness index, as well as the best measurement equipment. Most of these studies have focused solely on pavements. About 90% of the states in the United States (US) have a pavement smoothness specification, but only a few have a bridge smoothness specification. Recently, several more states have shown interest in developing a smoothness specification for bridges.

Although bridges account for a small percentage of the driving surface (compared to pavements), bridge smoothness is still a very important issue because bridges tend to be much rougher than pavements. This roughness can cause severe discomfort to the highway user. In recognition of the importance of this issue, the Illinois Department of Transportation (IDOT) initiated an effort to develop a bridge smoothness specification in 1999. A literature review of smoothness indices, as well as the different pieces of equipment available, was performed. In order to choose a proper smoothness index range for bridges, 20 recently constructed or rehabilitated IDOT bridges were tested using a lightweight profiler. International Roughness Index (IRI) and Profile Index (PI) were computed from field data.

This study first evaluates the various smoothness indices and their applicability to bridges, then evaluates various types of measurement equipment, presents the results of the field experiment, and presents a draft smoothness specification for bridges.

2. SMOOTHNESS INDEX

The accuracy and type of index chosen to evaluate bridge smoothness is related to the type of smoothness-measuring equipment chosen. In fact, the most important consideration in selecting the smoothness-measuring equipment is the selection of an appropriate smoothness index for use in the smoothness specification. Therefore, a discussion of the various smoothness indices will be presented first.

Pavement smoothness indices can be divided into the following categories (Smith et al., 1997): subjective ratings, mechanical filter-based, and profile-based. Subjective rating indices will not be considered here, since specifications must be based on objective, repeatable data. Nevertheless, the correlation of subjective ratings (user response) with objective smoothness measurements is an important factor in the selection of a smoothness index.

2.1. Mechanical Filter-Based Indices

Two of the most important mechanical devices for evaluating roughness are those based on response-type road smoothness and rolling straightedge systems. The Mays Ride Meter is one of the most popular Response-Type Road Roughness Measuring (RTRRM) devices. Such devices measure the cumulative vertical displacement between the axle and the vehicle body. The smoothness index is calculated by dividing the cumulative average vertical displacement by the traveled distance. According to Smith et al. (1997), Gillespie et al. reported in 1980 that the output of the Mays Ride Meter correlates better with user response than any other RTRRM system.

The PI is a mechanical filter-based index derived from profilogram equipment. It has shown some correlation with user response. In addition, it is highly accepted by highway officials and contractors across the US for smoothness control specifications. The profilograph uses a mechanical rolling straightedge filter. This device measures wavelengths varying from 1 to 25 ft (0.3 to 7.6 m) and amplifies or attenuates these wavelengths. When the PI statistic is used, longer wavelengths are attenuated and shorter wavelengths are amplified (Smith et al., 1997). A disadvantage of the profilograph is that it does not measure the true profile of the pavement surface. With a true profile, several other indices can be derived, such as IRI and Ride Number (RN). PI can be derived directly from the California profilograph or equivalent device, or it can be obtained by computer modeling using the true pavement surface profile. This is done using filters or other computer software, which simulates the profilograph trace. Another problem with the PI is that it is can be significantly affected by vertical curves, and many bridges are constructed on vertical curves.

2.2. Profile-Based Indices

Profile-based indices are obtained using two approaches: mechanical simulation of the response of a RTRRM system, or filtering and weighting the wavebands of the surface profile. Profile-based indices can be measured by different types of instruments. According to Sayers and Karamihas (1998), four basic steps must be followed to compute a profile-based smoothness index. The fist step is to determine how many profiles are needed. Most indices require only one profile, but some indices are calculated from two profiles. The second step is to filter the measured profile. The third step is to reduce the sequence of transformed numbers obtained in the previous step to a single index, which can be obtained by accumulating absolute or squared values. Finally, the last step is to convert the index obtained in step 3 to an appropriate scale to normalize the smoothness index. This usually involves dividing by the number of profile points or the length of the profile.

Among the profile-based indices, the IRI is the most widely used by far. According to Sayers (1995), it has evolved over many years in the following three stages: quarter-car simulation on high-speed profilers, National Cooperative Highway Research Program (NCHRP) research on response-type road roughness measuring systems, and World Bank development of the IRI. The National Cooperative Highway Research Program (NCHRP) research concluded that the *Golden Car* provided the best correlation with response-type systems. The Golden Car is a model with a set of mathematical parameter values for springs and shock absorbers used in vehicle simulation.

An experiment was conducted in Brazil in 1982 to find a suitable index and to quantify the relationships between different equipment and roughness indices in use (Sayers et al., 1986). The International Road Roughness Experiment (IRRE) was conducted by research teams from Brazil, the United Kingdom, France, the United States, and Belgium. Forty-nine road test sites were measured using a variety of test equipment and measurement conditions. The sites included a full smoothness range of asphalt concrete, surface treatment, gravel, and earth roads. The data acquired were analyzed to determine the extent to which the different types of equipment could be used to obtain a common measure of smoothness. Also, it determined how the different measures of smoothness could be related quantitatively for common use. This experiment proposed that IRI should be used as the standard smoothness index and concluded that IRI can be well correlated with the measurements obtained with RTRRM systems.

IRI is obtained by computer simulation of a virtual response-type system using a mathematical model (Sayers and Karamihas, 1998). In other words, IRI is a mathematical transform of a true profile using a computer program. The virtual response-type system used to calculate IRI is a quarter-car model set at the Golden Car parameters, such as a relationship between mass and rates (spring and damper), and a speed of 49.7 mph (80 km/h), as shown in Figure 1.

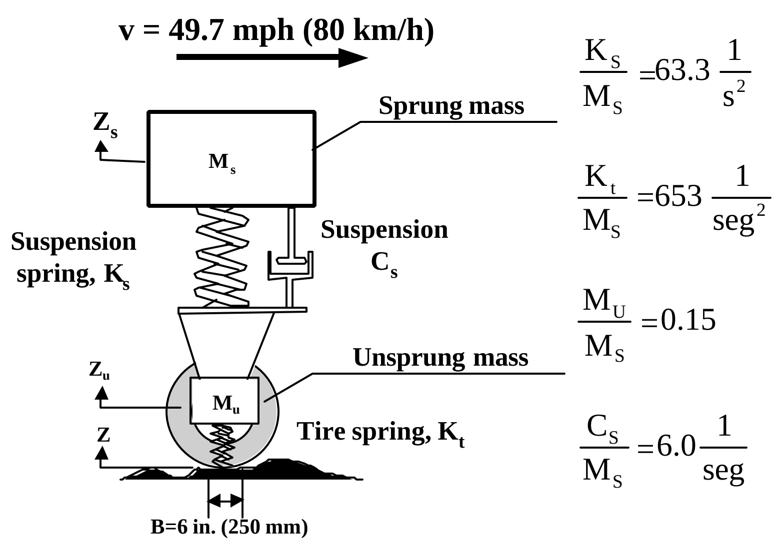

Figure 1. Virtual model used to calculate IRI

The steps used to calculate IRI are described according to Sayers and Karamihas (1998). A moving average filter with a base length of 9.85 in (250 mm) is applied to one measured true profile. The moving average is a low-pass filter that smoothes the profile. The computer program does not apply the filter if the profiler interval is greater than 6.6 in (167 mm). The moving average filter should be omitted if the profile has already been filtered and the sample interval is less than 6.6 in (167 mm). K.J. Law profilers have sample intervals of 1 in (25 mm), but store the results at intervals of 6 in (150 mm), after applying a 12-in (300-mm) moving average filter. Therefore, the moving average should not be applied when K. J. Law data at 6 in (150 mm) is used to calculate IRI. According to Sayers (1995), the difference between the 9.85-in (250-mm) and the 12-in (300-mm) moving average filter used by K. J. Law on IRI is negligible. The profile is then filtered again with the Golden Car filter, which simulates the suspension motion. IRI is the accumulated summation of the elevation absolute values of the resulting profile. It is simply the quotient of the vehicle frame divided by its length. Therefore, IRI has dimension of vertical movement of the standardized vehicle from over a given length of pavement per horizontal length and units of in/mi or m/km.

Another explanation of IRI is given by Smith et al. (1997): IRI is defined as the Reference Average Rectified Slope (RARS) of a standard quarter-car simulation at a speed of about 50 mph (80 km/h), measured in units of length per length. As IRI is derived directly from the true surface profile, it can be measured with any valid profiler. Also, IRI correlates fairly well with user response (Al-Omari and Darter, 1994).

Other smoothness indices that use a quarter-car filter are RARS and RN developed by Sayers (Sayers and Karamihas, 1998). Some profile-based indices that require filtering and weighting the wavebands of the surface profile include the Michigan DOT Ride Quality Index (RQI), the quarter-car index (QI) and some RNs, such as Janoff and Spangler (Sayers and Karamihas, 1998). Therefore, RNs are pavement profile-based indices, except the Mays Ride Number. Some of them have shown very good correlation with user response. The primary disadvantage of RNs is that they are fairly new and are not widely accepted yet. Further testing is required to determine correlation between RNs and other pavement smoothness indices.

In the 1980's, two NCHRP projects resulted in RNs. The objective of these projects was to determine how the road profiles correlate with user response (Sayers and Karamihas, 1998). During these studies, the Mean Panel Ratings (MPRs) were determined for several roads, and profile-based analyses were performed to predict the MPRs. Therefore, the RN originated, and is an estimation of the MPR.

In 1992, the Federal Highway Administration (FHWA) sponsored a study titled, "Interpretation of Road Roughness Profile Data." This study compared RNs obtained from different types of profiler measurements on the same pavement. To develop a new algorithm to compute RN, data were used from three experiments in which panel ratings were obtained for roads that had been profiled in both the left and the right wheel paths. These experiments were held in Ohio in 1983 and 1988 and in Minnesota in 1993 (Sayers and Karamihas, 1996). The new algorithm for computing is almost the same as the one used to calculate IRI. Therefore, the existing software for computing IRI can be changed slightly to calculate RN as an output option. The importance of the new algorithm is its good correlation with MPR (R^2 = 0.85). In the NCHRP study conducted by Janoff, it was reported that the correlation between MPR and a half-car index, similar to IRI, is significantly inferior to the correlation with RN. This correlation is even lower for PCC pavements (Sayers and Karamihas, 1996). However, Al-Omari and Darter (1994) found that the correlation between MPR and IRI was the same for asphalt pavements, concrete pavements, and asphalt overlays of concrete pavements. These data were obtained from six states and were quite comprehensive.

3. EQUIPMENT

A literature review about the types of measuring equipment was conducted to determine the most suitable device to evaluate smoothness of new bridges. Different types of equipment and manufacturers have different capabilities. Such capabilities were compared to decide which equipment should be used. Aspects taken into account in the assessment included speed, roughness parameter capability, and applicability for new construction.

3.1. Required Characteristics

Smith et al. (1997) enumerated the characteristics that measuring equipment must have to obtain reliable smoothness indices. These recommendations are related to the capabilities of the equipment. Therefore, in order to use certain equipment, it must comply with various requirements, as shown in the following paragraphs.

The selected equipment must be able to accurately measure a range of wavelengths, which depends on the measured index. For instance, to measure IRI the equipment must be able to measure wavelengths from 2.1 to 110 ft (0.6 to 33.5 m), whereas to measure PI the equipment must measure wavelengths that range from 0.9 to 85 ft (0.3 to 25.9 m). Consequently, to measure IRI and PI using the same equipment, it must be capable of accurately measuring wavelengths from 0.9 to 110 ft (0.3 to 33.5 m).

The sampling interval is a function of the minimum wavelength of interest. According to Smith et al. (1997), a certain sampling theorem (Shannon) suggests that the sampling interval must be at least two times the minimum wavelength of interest. The importance of requiring a minimum sampling interval is to avoid a phenomenon called "aliasing" of the profile, which causes the frequencies to be mistaken due to the addition of phantom long wavelengths to the profile. The sampling interval is also a function of the type of anti-aliasing filter used in the analysis. If the smallest wavelength of interest is 0.9 ft (0.3 m), the sampling interval should be 2 in (50.8 mm) for an analog filter and 1 in (25.4 mm), for a digital filter.

Longitudinal accuracy is also required to find must-grind locations and for correlating the outputs from repeated passes. Smith et al. (1997) recommended a maximum value of 0.10 percent error for the initial smoothness equipment specification. This is the level of accuracy of the standard profilograph, which has been an acceptable value. Also, there is available technology for the newer equipment that meets this specification.

It is also required that equipment for measuring initial pavement smoothness must have enough vertical elevation accuracy. Accuracy is comprised of two parts: precision and bias. The first is the repeatability of several pieces of equipment using several operators, whereas the second is the deviation of the measured value from the actual value. Vertical elevation accuracy can be measured both statically and dynamically. Smith et al. (1997) recommended a static accuracy value of 0.005 in (0.13 mm) for precision and bias. They recommended a dynamic accuracy of 0.015 in (0.38 mm) for precision and 0.050 in (1.27 mm) for bias.

The footprint plays an important role when comparing high-speed inertial profilers. Smaller footprints can get lost in pavement cracks or bridge joints, which will yield an inaccurate profile. On the other hand, larger footprints are less likely to penetrate pavement cracks. According to Smith et al. (1997), infrared measurement devices generally have a much larger footprint than laser devices, and therefore tend to provide better results. Another major consideration is the operation speed. Slow hand-operated equipment requires longer lane closures and considerably more operating time. High-speed profilers require much less operating time and may not require lane closures.

3.2. Types

There are several types of devices available to evaluate road smoothness. These devices can be grouped into two main categories: profilers and response-type. Profilers are used to produce a series of numbers related to a true profile (Sayers and Karamihas, 1998). They work by combining a reference elevation, a height relative to the reference, and a longitudinal distance. Some devices included in this category are rod and level, dipstick, and inertial profilers. Profilers collect data much faster. When response-type devices are used, only one index can be obtained.

In response type equipment, a vehicle is instrumented with a transducer (called a road meter) to record suspension movements and evaluate smoothness. The road meter produces a smoothness reading as the result of the vehicle motions that occur while traversing the road. This piece of equipment offers a means to rapidly acquire smoothness data with relatively inexpensive equipment. This measurement is closely tied to vehicle response, time, weather, and other factors (Sayers et al., 1986). In general, RTRRM system measurements are less accurate and require fairly complicated calibration to convert them to a standard scale.

The description of most equipment considered in this section is based on the NCHRP 1-31 report (Smith et al., 1997). At that time, the California-type profilograph was suggested as the best equipment to use for an initial pavement smoothness specification. However, the inertial pavement profilers were recognized to provide a better representation of pavement profile. Inertial profilers were not recommended for measuring initial pavement smoothness because of their high cost and inability to test concrete pavement at early ages. Since that study was completed in 1995, the use of lightweight profile-measuring devices has rapidly expanded. More experience with such devices has been gained, allowing their use in pavement smoothness specifications. This type of equipment has overcome the drawbacks of full-size inertial profilers, that is, high cost and inability to test young concrete. According to a Hometown Journal (1999), the use of lightweight profilers to determine the smoothness of newly constructed pavements is the object of a cooperative study between FHWA and the DOTs of six states (Connecticut, Indiana, Minnesota, Arizona, Oregon, and Arkansas).

3.2.1 Straightedge - Stringline

A straightedge or stringline is a basic method of identifying pavement irregularities. This device is usually made of wood or metal and has a typical range of 8 to 16 ft (2.4 to 4.9 m). Irregularities are controlled by a maximum variation measured when the straightedge is placed on the pavement surface. This method requires time. Therefore, continuous longitudinal pavement profile using this device is not practical. Its application is limited to short wavelength roughness, since its accuracy is diminished if the wavelength roughness is greater than one-half of its length, that is, 4 to 8 ft (1.2 to 2.4 m). Some state agencies use the straightedge along with other types of smoothness control.

3.2.2 Rolling Straightedge

A rolling straightedge is basically a rigid beam with three wheels: one at each end and one at the midpoint. The wheel located at the midpoint is connected to an indicator that shows the deviation from the straightedge plane. This approach also takes time and cannot measure the true profile. According to Collins et al. (1996), this device measures short wavelength surface deviations but is unaffected by longer surface dips and undulations, which are perceived by drivers as roughness. This is one of the reasons it was not used in Georgia DOT construction specifications to measure and control pavement smoothness.

3.2.3 Auto Rod and Level

The auto rod and level is used primarily for airport pavements. It has a pushcart with a rod that is linked to a laser transit and records rod and level type measurements, as shown in Figure 2. This device can produce an actual profile of the bridge deck at walking speeds.

Figure 2. Auto rod and level

3.2.4 Inclinometer-Based Profiler

Sensitive inclinometer sensors have been used in three manually operated profilers. Two of these profilers will be briefly discussed in the following paragraphs: Walking Profiler and Rolling Dipstick®.

Walking Profiler

The Australian Road Research Board (ARRB) developed and manufactures the Walking Profiler. A picture of this device can be seen in Figure 3. The operating speed for this unit is only 0.73 ft/s (0.22 m/s) with a sampling interval of 9.5 in (241 mm). The vertical and horizontal deviations from the starting point are stored in an onboard laptop computer. The profile accuracy reported by the manufacturer is +/- 0.04 in/1500 ft (0.1 cm/457.2 m). The benefit of using this device is that it measures the true profile. Therefore, most indices such as IRI, RN, and PI can be derived from its output. Another benefit is that it can be used on recently poured concrete slabs due to its lightweight. The problem with this unit is the very slow operating speed and large sampling interval.

Rolling Dipstick®

The Rolling Dipstick® is a rolling profiler developed by the Face Companies (Figure 4). The maximum operating speed is 1.8 ft/s (0.54 m/s), but a slower mode should be used for better accuracy. The sampling interval is 9.8 in (250 mm), and the profile accuracy is about +/- 0.01 in/25 ft (0.025 cm/7.6 m), as reported by the manufacturer. This is one of the most accurate devices to measure the true profile, but it is slow and has a large sampling interval. Due to its accuracy and low operating speed, it is mostly used to calibrate other types of smoothness measuring devices.

Figure 3. Australian Road Research Board (ARRB) Walking Profiler

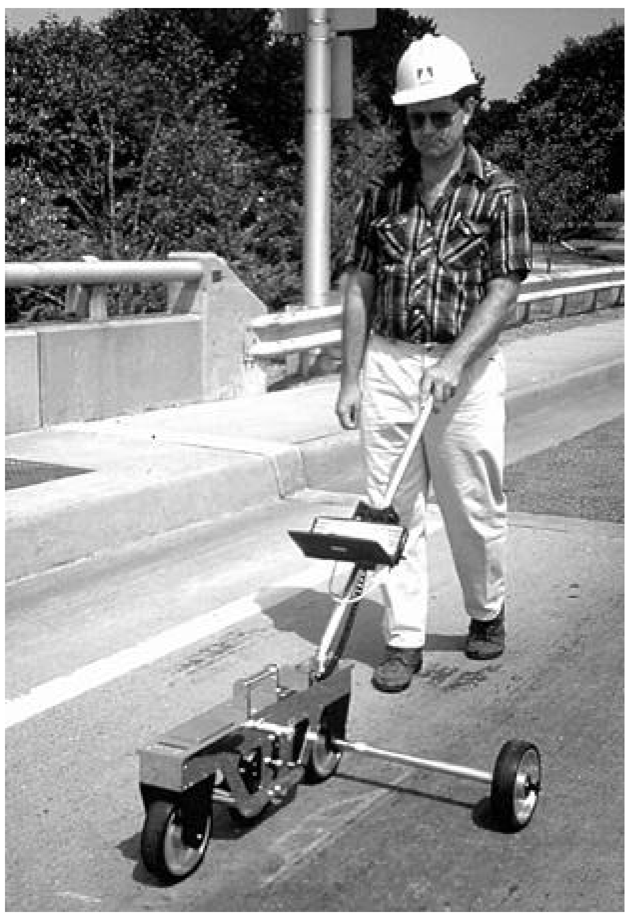

Figure 4. Rolling DipstickÒ

3.2.5 Profilograph

Profilographs consist of a rigid frame carried by several wheels placed over the pavement surface; the wheel located in the middle of the rigid frame is called the *profile wheel*. Vertical movement deviations of the profile wheel, with respect to the data provided by the system of wheels, are recorded in the form of a strip chart mechanically or by computer. This is not the true surface profile of the pavement. The strip chart provided by the mechanical models can be evaluated manually or electronically, whereas the computerized models produce a strip chart automatically. There are a variety of profilograph models, which differ basically in the support wheel system configuration. The speed at which they operate ranges from 2 to 3 mph (3.2 to 4.8 km/h). Only the California profilograph will be discussed in detail.

The California profilograph has been the most widely used roughness measuring device for pavement smoothness specifications. Spans varying from 10 to 30 ft (3.0 to 9.1 m) have been used, but the 25-ft (7.6-m) long version became popular during recent years. The interpretation of the strip chart provided by this equipment results in the PI, which has a dimension of length per length (in/mi or m/km). This index represents the total accumulated profile beyond a limit zone per traveled distance. The limit zone, called blanking band, varies from 0 to 0.2 in (0 to 0.5 cm). There is also an allowable limit for individual bumps, which is usually 0.3 in (0.8 cm) but can be up to 0.5 in (1.3 cm), depending on the agency. If the allowable specified value for individual bumps is exceeded, the bump should be removed using grinding. The major benefit of the California profilograph is that it is widely used and accepted by the highway and contracting community around the country. Smith et al. (1997) reported that about 60% of the states in the US use the California-type profilograph for measuring initial pavement smoothness. A picture of this equipment is shown in Figure 5.

Figure 5. California profilograph

Although the profilograph has been used extensively, there are several concerns with using this equipment for new bridge pavement specifications. The slow operating speed of the profilograph (2 to 3 mph or 3.2 to 4.8 km/h) makes measurements time consuming and requires lane closure if the facility is opened to traffic. Recent studies have also shown that the precision and repeatability of the profilograph are questionable. According to Smith et al. (1997), an Arizona DOT study showed that the average standard deviation can be as high as 1.9 in/mi (0.03 m/km), while some incentive/disincentive pavements are based on smaller increments. Even the reproducibility of the results was not good: the range of the measured PI using the same operator was between 3.5 and 7.0 in/mi (0.06 to 0.11 m/km) for a smooth section and between 7.0 and 11 in/mi (0.11 to 0.17 m/km) for a rougher section. Another concern with the profilograph is that it only measures the PI and cannot be converted into any other index since it does not provide a true surface profile. Since the profilograph amplifies and attenuates the true pavement surface profile, there have also been concerns about its correlation with the wavelengths that are felt by highway users.

Another issue with the profilograph is potential problems of measurement of vertical curves, which include most bridges. Even if the profile were exactly correct according to the vertical curve profile, the PI may not show a corresponding zero value due to the geometrics involved between the profilograph and vertical curve of the bridge deck.

There are a variety of California profilograph manufacturers, such as Ames, James Cox & Sons Inc., and Paveset. Ames offers a California style profilograph that uses a box beam in its span, instead of a truss type design. This device meets the normal California profilograph standards and both manual and computerized models are available. James Cox & Sons Inc. are pioneers in the development of profilograph technology. They offer a standard truss type California style profilograph. They make computerized profilographs and no longer make manual profilographs. Paveset has developed a profilograph that can be towed behind a vehicle operating at a speed of 5 mph (8.0 km/h). A picture of this equipment can be seen in Figure 6.

Figure 6. California profilograph developed by Paveset

3.2.6 Response-Type Road Roughness Measuring (RTRRM) Systems

Roughness is evaluated by using a mechanical device placed over the pavement surface to measure the dynamic response due to irregularities. The vertical movement of the vehicle axle with respect to its frame is measured and used to calculate IRI. One of the primary advantages of RTRRM systems is that they are cost-effective. Although they have a high calibration cost, they have an overall low initial and operational costs, and they run at traffic speed (50 mph or 80 km/h). In addition, they produce reasonably accurate results if properly maintained and calibrated. The calibration is very important but not straightforward, since roughness measurements are affected by several components, including the characteristics of the mechanical system and the operating speed. This device must be frequently calibrated using known profiles that range from smooth to rough, at a variety of operating speeds. Another disadvantage is that this equipment does not provide the true pavement profile, but only the difference between the vehicle frame and vehicle axle.

The most known RTRRM system device is the Mays Ride Meter (MRM). It produces a strip chart in response to the pavement irregularities from which the roughness is analyzed. The parameter used to evaluate pavement smoothness is called the Mays Ride Number (MRN). This number is affected by the travel speed, which varies between 20 to 60 mph (32 to 97 km/h). Some characteristics of the host vehicle also affect the results, such as tire pressure, suspension system, and vehicle weight. Because the MRM results are affected by all the factors discussed previously, there are concerns about the accuracy and repeatability of such devices for initial pavement smoothness control. There is no temperature correction to the Mays Meter results, but testing is not allowed below 0^{o}C.

3.2.7 Inertial Profiler

Inertial profilers have recently become available from several manufacturers across the nation. There are two kinds of inertial profilers: full-size and lightweight. Their technology is the same. They measure the longitudinal profile using accelerometers located in the body of the measuring vehicle to create an inertial reference. As a result, they yield a true longitudinal profile of the road surface, which can be filtered (to remove longer built-in vertical curves) and analyzed by computing several available smoothness indices.

Inertial profilers can differ in the mechanisms to measure the relative displacement between the accelerometers and the surface of the pavement. Some devices utilize a light-based measuring system, either laser or infrared, to measure the distance to the surface. The infrared-based systems have a larger footprint than the lasers and therefore have less of a tendency to get lost in microstructure and bridge joints.

Full-Size Inertial Profiler

The most important advantage of the full-size inertial profiler is that they operate at normal highway speeds of 50 to 60 mph (80 to 97 km/h). The drawback of this type of equipment is that it cannot be used on recently placed concrete pavements and bridge decks due to its weight. Another disadvantage of the full-size inertial profiler is that it is much more expensive than the other types of equipment. Another issue could be accessibility and operating area concerns with newly constructed bridges that do not have sufficient approaches for the vehicle to maneuver.

Inertial profiler technology became available in the 1960's. The first contact-type profiler was manufactured by K. J. Law in 1966 for Texas DOT. In 1979, K. J. Law released the model 690 SDP (Surface Dynamics Profiler), and later the model 690 DNC (Digital Non-Contact). In 1994, the 690 DNC model was replaced by the T6600 model, which also measures the rut depth in each wheelpath. Some parameters provided by this equipment are IRI, NCHRP 1-23 and ASTM Ride Numbers, Root Mean Square Acceleration (RMSA), and MRN. The manufacturer estimates profile repeatability to be 0.02 in (0.5 mm), and the distance measuring accuracy is 0.01%. Later, the model T6600 was replaced by the model T6500.

Another full-size inertial profile was developed by Australian Road Research Board (ARRB) Transport Research. Their equipment is a portable laser based device and is attached to a vehicle for high-speed operation. They provide profiling systems to fit customer requirements. The One-, Two- or Three-Laser Profiler is a portable, towbar mounted system for measuring road roughness by recording representative profiles of the road surface at highway speed. A dual laser profile is shown in Figure 7. The profiler comes with an onboard computer, conditioning electronics, odometer system, and a range of software for data acquisition and analysis. ARRB Transport Research also developed a Multi-Laser Profiler (MLP), which is a vehicle-mounted system that automatically collects integrated road condition data by recording laser profiles of the road surface at highway speed. A picture of this device is shown in Figure 8. The MLP comes with an onboard computer system and a range of software for data acquisition and analysis tasks.

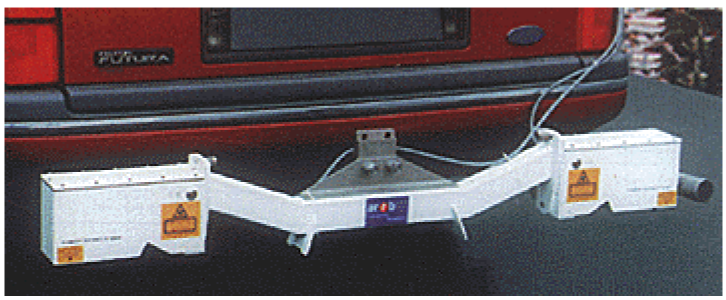

Figure 7. Dual laser profiler

Figure 8. Multi-laser profiler

South Dakota DOT developed a profiling system in 1981 (Smith et al., 1997). Accelerometer and ultrasonic sensors are placed in the front of the inertial vehicles for profile measurement in one wheel path. Profile elevation measurements are taken at 1-ft

(0.31-m) intervals, and the testing speed can range up to 65 mph (105 km/h). It generates PSI, IRI, and Mays Output values. In 1990, Georgia DOT started using the South Dakota Profiler to evaluate pavement smoothness (Collins et al., 1996). In 1995, GDOT acquired eight laser-based South Dakota type Profilers to begin the replacement of the Mays Meter trailers as the measuring tool for the GDOT Ride Quality Program. Correlation between the Mays Meters and the South Dakota type laser based Profilers is reported to be very good.

Dynatest also manufactures a high-speed device, which measures the cross-sectional profile and longitudinal surface profile. Using a combination of accelerometers and laser sensors, this equipment can generate longitudinal profile for each wheel path at intervals down to 1 in (25.4 mm) and at a speed of up to 62 mph or 100 km/h (Smith et al., 1997). This equipment can provide a response-type smoothness index developed at the University of Texas and IRI values for each wheel path. Its picture is shown in Figure 9.

Figure 9. Dynatest profiler

Lightweight Profiler

Although lightweight profilers cannot operate as fast as the full-size, they can be used right after construction. Their speed still requires lane closures but drastically reduces operating time as compared with hand-operated devices. Since lightweight profilers measure true profile, indices such as the IRI, PI, and RN can be calculated from the output. AMES, International Cybernetics Corporation (ICC), and K. J. Law are some of the lightweight profiler manufacturers.

The AMES lightweight profiler uses a laser sensor and provides accurate measurements if the pavement length ranges between 1.8 and 314 ft (0.55 and 95.7 m). According to the manufacturer, it has an operating speed that varies from 5 to 15 mph (8 to 24 km/h), a continuous sampling rate, a vertical resolution of 0.001 in (0.025 mm), a storage interval of 3 in (76.2 mm), vehicle weight of 950 lb (431 kg), and an effective ground pressure of 6 psi (0.041 MPa). The International Cybernetics Corporation (ICC) lightweight profile is also a laser-based system and also provides continuous coverage sampling. According to ICC, the profile sampling is 1 in (25.4 mm), the profile repeatability is 0.014 in (0.35 mm), and it has an absolute bias of 0.045 in (1.12 mm). The laser sensor resolution is 0.002 in (0.05 mm) and has a footprint of 0.06 in $\times$ 0.08 in (1.5 mm $\times$ 2.0 mm).

On the other hand, the K. J. Law lightweight profiler is an infrared-based device. According to K. J. Law Engineers Inc., its operating speed ranges from 10 to 25 mph

(16 to 40 km/h). One of the benefits of this profiler is that it uses an infrared measuring system with a larger footprint than the laser devices, providing better results (Sayers et al., 1997). The sensor footprint is 0.24 in $\times$ 1.46 in (6 mm $\times$ 37 mm), which simulates tire contact area better than the laser-based devices. This equipment has a 1-in (25.4-mm) sampling interval, a profile repeatability of 0.02 in (0.5 mm), and the profile absolute bias is 0.05 in (1.25 mm).

3.3. Comparison between Different Smoothness Measuring Devices

Some experiments have been performed to evaluate how different devices produce a given index. For instance, El-Korchi and Collura (1998) reported a study that attempted to evaluate the IRI produced by high-speed profilers owned by New England state highway agencies (SHAs) comparable to the reference IRI calculated using the Face Dipstick® to measure the profile. Equipment from other SHAs, such as Connecticut, Massachusetts, New Hampshire and Vermont, was also evaluated in the study. In all, the following devices were used in this study: four high-speed profilers (three ARANs and one K.J. Law), one Mays Ride Meter, and one Face Dipstick® 2000 model. This study concluded that little correlation existed between the IRI produced by the high-speed profilers and the IRI produced by the Dipstick®. The tested ARAN profilers produced an average IRI lower than the Dipstick® IRI, whereas the average IRI values produced by the K.J. Law Profiler were higher than the Dipstick® IRI values. The Mays Meter IRI values were also higher than the Dipstick® IRI values. The speed effect of the high-speed profilers on the average IRI statistic was also evaluated and reported to be very small. The precision of all profilers was analyzed and appears to be excellent.

4. FIELD TESTING OF BRIDGES

This section describes the experiment conducted to produce the bridge smoothness specification for IDOT. The selection of the index and equipment will be discussed first, followed by the description of the test procedure. Then, the analysis and results will be presented.

4.1. Index and Equipment

As discussed before, there is an intrinsic relationship between smoothness index and the type of smoothness-measuring equipment. Therefore, an index must be selected depending on the availability and capability of equipment to measure the selected index.

According to Smith et al. (1997), some factors that should be taken into account when selecting a pavement smoothness index are good correlation with user response, ability to be correlated with other smoothness indices, and past experience with the selected index.

Smith et al. (1997) selected IRI and PI as the best indices to evaluate pavement roughness. At that time, PI was the most widely used smoothness index to evaluate new pavements. However, with the current widespread availability of the lightweight profilers, the ability to obtain an IRI is no longer a problem. Also, the IRI has been shown to correlate well with highway panel ratings, and the correlation is the same for asphalt pavements, concrete pavements, and asphalt overlay of concrete pavements. These analyses were based on hundreds of measurements in the US (Al-Omari and Darter, 1994). The great advantage of lightweight equipment is that it allows measuring the true profile right after construction, at a considerable speed. Since IRI correlates reasonably well with user response and is based on the true profile, it is the recommended smoothness index to be used in developing the smoothness specification. In addition, IRI is the index commonly used to evaluate smoothness for pavement management purpose. According to Hajek et al. (1998), the use of IRI to report pavement smoothness has been mandatory since 1987 in the US for the Highway Performance Monitoring System. Therefore, it is better to use IRI to evaluate smoothness for new pavements and bridges, since this will allow direct correlation with pavement management data. Full-size inertial profilers are used to evaluate roughness for pavement management purposes, in view of the fact that they provide the fastest evaluation. However, the IRI values obtained are similar to that obtained with the lightweight profilers.

A survey among 45 State Highway Agencies (SHAs) showed that three of these states (Massachusetts, Rhode Island, and Vermont) did not have any type of smoothness specifications (Ksaibati et al., 1995). This showed that there is a variability of opinion on which PI values indicate smooth or rough roads among the surveyed agencies. It also shows that most of the SHAs believe their smoothness specifications are good or very good. Only two states indicated poor satisfaction with their smoothness specifications. Regarding the survey about equipment used for concrete pavement roughness control, 30 out of 42 SHAs that had a smoothness specification at the time of the survey used the California-type profilograph, whereas five SHAs used the Rainhart profilograph, one used the Mays Meter, and four used other devices. Three states (Alaska, Maine, and New Hampshire) reported that they did not build PCC pavements. Regarding the survey about equipment used for asphalt pavement smoothness control, 15 SHAs used the California profilograph, 16 used some form of straight edge, five states used the Mays Meter, and four states used another type. At that time, most SHAs used the California profilograph to accept pavement smoothness.

Some cities have attempted a correlation between IRI and some other index so that they could retain historical roughness data. For instance, the Ministry of Transportation of Ontario (MTO) has used a response-type index measured using the Root Mean Square Vertical Acceleration (RMSVA) of a trailer axle for 10 years, but lately some attempt has been made to switch to profile-based IRI. Hajek et al. (1998) published correlation between IRI measured using a full-size profiler and the ride condition index used by MTO during their attempt to switch to IRI to monitor pavement roughness.

An important characteristic of the profiler is that it allows computing of several smoothness indices, since it is based on the true profile. This differs from the California profilograph which can yield only PI data, since it is based on the relative profile. Therefore, IRI and RN data cannot be obtained using a profilograph. Another disadvantage of the California profilograph is that its results are distorted when a bridge is on a vertical curve.

Several pieces of new lightweight profile equipment produced by different manufacturers were considered at the beginning of this research. The equipment chosen for conducting these tests was the K.J. Law T-6400 Lightweight Profiler (Figure 10). This equipment was selected because of its leasing availability, the manufacturer's reliability, and for its accuracy, speed, and sampling interval. It was obtained under a contract from Resource International, of Columbus, Ohio, to test the specified IDOT bridges, during a maximum of 7 days. Resource International also supplied an engineer and technician to operate the equipment and to transport it between test sites. A staff member from the University of Illinois was present and assisted with the testing of all bridges. Several IDOT personnel also observed the testing.

Figure 10. Lightweight profiler

The equipment was used to obtain smoothness data on the selected bridges over a period of 3 days. The measurements were taken at a speed of 20 mph, and a sampling interval of 1 in (25.4 mm).

4.2. Testing Procedure

IDOT provided a list of 33 bridges in and around Springfield, Illinois, for possible test locations, as listed in Appendix A. From this list of bridges, 20 were selected as a representative sampling of the different types of bridges used in Illinois.

During the tests, cones with reflectors were used to set the beginning and end of the test section. These cones were set up 150 to 200 ft (45.7 m to 61.0 m) ahead of and behind the bridge approach slabs, depending on the span and approach length of the bridge. Appendix B shows the total length of all 20 selected test sections, as well as their separation into front existing pavement, deck plus approach pavements, and rear existing pavement.

Once the reflective cones were in place and traffic control was set up, the K.J. Law T-6400 was run along each wheel path of the right hand lane (driving lane) of the bridge being tested. Each wheel path was run once in the direction of traffic for most of the bridges. In order to evaluate the repeatability of the equipment, three bridges were tested several times in each wheel path. The data were automatically collected in the onboard computer and stored for analysis. The data were originally in binary form, but they were converted into text files using the K.J. Law software. These text files were used in Excel and also converted into ERD format for analysis.

4.3. Results and Analyses

This section presents all results obtained from the tests performed. The nomenclature of the test sections is presented first. Then, the repeatability of the profile measured by the lightweight profiler is analyzed. After that, the IRI and the PI are presented for the entire test sections.

4.3.1 Separation of the Profile Data

The full profile analyses include the entire data set collected for each bridge. These analyses are representative of the ride quality felt by the driver as a car passes over the bridge. Figure 11 shows the true profile of the entire tested section of bridge number 069-0055, divided into five subsections.

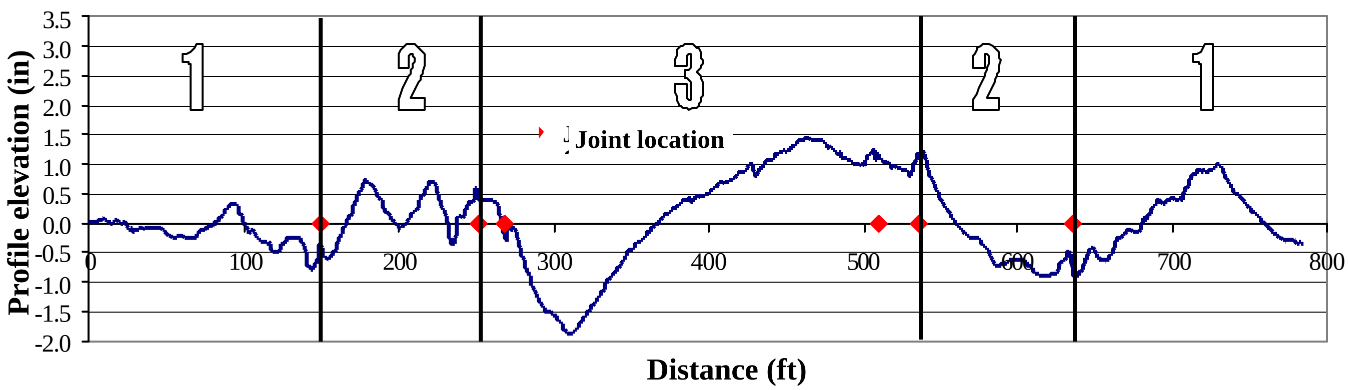

Figure 11. Division of the test section of bridge number 069-0055 into five subsections

The five subsections shown in Figure 11 are front existing pavement, front approach pavement, bridge deck, rear approach pavement, and rear existing pavement. The length of the front and rear existing pavements, and the length of the bridge deck, combined with the approach pavements, for all 20 bridges in the study are shown in Appendix B. The typical IDOT design of a bridge approach slab is shown in Figure 12 when the bridge is connected with an asphalt pavement and in Figure 13 when the bridge is connected with a concrete pavement. It is observed that a bridge approach pavement is usually a slab 30 ft (9.1 m) long. Each of the five subsections considered in Figure 11 are explained, as follows:

1 – Existing pavement. This subsection varies between 150 and 200 ft (45.7 and 61.0 m), depending on the bridge span, as shown in Appendix B. There are two existing pavements designated as front and rear. For a new bridge, the pavement connector should be included in this section, as shown in Figure 12 for asphalt pavements and in Figure 13 for PCC pavements. The front existing pavement is the pavement leading up to the first bridge joint, whereas the rear existing pavement is the pavement following the last bridge joint.

2 – Approach pavement. There are two approach pavements designated as front and rear. In the IDOT typical bridge design, the length of the approach slabs is usually 30 ft (9.1 m), as shown in Figure 12 for asphalt pavements connected to the bridge, and in Figure 13 for concrete pavements connected to the bridge. The joints were determined using the profiler event marker and may not precisely represent every joint. Also, some joints may not have been shown. The location of the joints, as well as their types, can be determined precisely in the bridge deck design plans.

3 – Bridge deck. This subsection is the bridge deck itself. Multiple spans are shown by pier locations. Its length correspond to the distance between the first and the last abutments. When the bridge has four abutments instead of two, the first and last abutments are called back abutments, and the second and the third abutments are called front abutments.

Appendix C shows the joints marked by the profiler operator during the tests, as well as the location of the piers and abutments according to the plans. The transition between the existing and approach pavements is also identified. The approach pavement length is located between the transition and the abutment. When the bridge has back and front abutments, the approach pavement length is the distance between the transition and the back abutments, as shown in Figure 11. It is observed from Appendix C that not all bridges have an approach pavement. Bridge number 084-0078, for instance, has been overlaid and it is not possible to distinguish the existing pavement from the approach pavement.

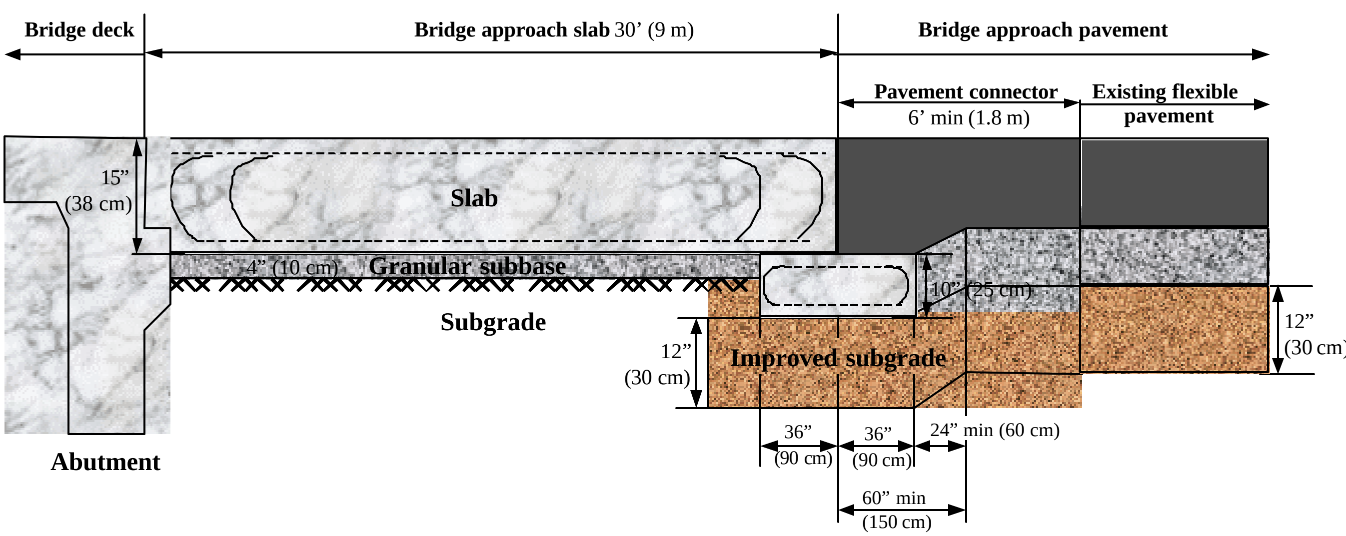

Figure 12. Typical IDOT design of a bridge approach slab connecting the bridge with asphalt pavement

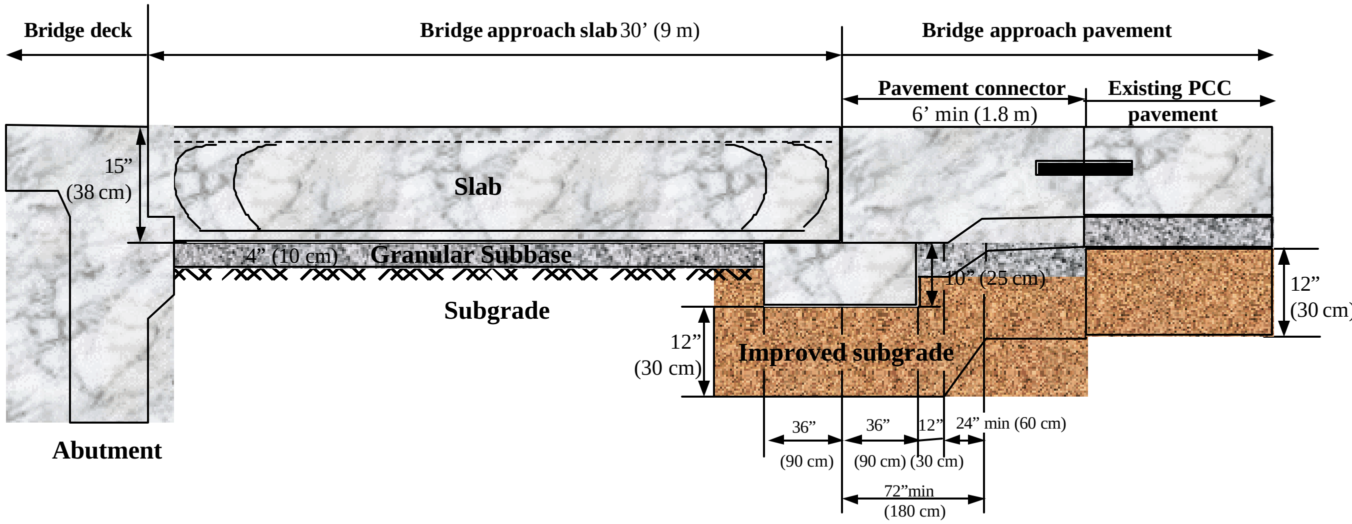

Figure 13. Typical IDOT design of a bridge approach slab connecting the bridge with concrete pavement

4.3.2 Repeatability

To test the accuracy of the lightweight profiler, three wheel paths from two bridges, 069-0043 and 069-0077, were tested several times. The results of these tests are shown in Appendix D. Table 1 shows the statistical data for the repeatability tests. For the right wheel path of bridge number 069-0043, the average IRI is 161 in/mi (2.54 m/km) and the standard deviation is 2.06 in/mi (0.03 m/km). The average IRI for the right and left wheel paths of bridge number 069-0077 is approximately the same: 145 in/mi or 2.29 m/km (right wheel path) and 147 in/mi or 2.32 m/km (left wheel path). The average PI for the right wheel path of bridge number 069-0043 is 46.1 in/mi (0.73 m/km) and the standard deviation is 0.55 in/mi (0.01 m/km).

Table 1. Statistical data for the repeatability analysis

Index	Statistics	Bridge Number		
		069-0043 (RWP*)	069-0077 (RWP*)	069-0077 (LWP**)
IRI	Average (in./mi)	161	145	147
	SD (in./mi)	2.06	1.26	1.91
	COV (%)	1.28	0.87	1.31
PI	Average (in./mi)	46.1	37.0	37.1
	SD (in./mi)	0.55	1.58	1.71
	COV (%)	1.20	4.26	4.61

*RWP: right wheel path
**LWP: left wheel path

The average PI for the right and left wheel paths of bridge number 069-0077 did not change (about 37 in/mi or 0.06 m/km), although the standard deviation is about 1.6 in/mi or 0.03 m/km (Table 1). It is observed from Table 1 that the covariance is about 1% for IRI statistics, but it can be as high as 4.6% for PI statistics. It is also observed that the standard deviation of PI statistics can be 1.7 in/mi (0.03 m/km), and most specifications have an incentive/disincentive increment of about 1 in/mi (0.02 m/km). This analysis shows that IRI statistics are more repeatable than PI statistics when the lightweight profiler is used to calculate these indices.

The profiles obtained with the repeatability tests were plotted on top of each other for comparison. Figure 14 shows the profile provided by the K.J. Law Profiler for the right wheel path of bridge number 069-0043. This is not the true profile, since it has been filtered using a moving average filter.

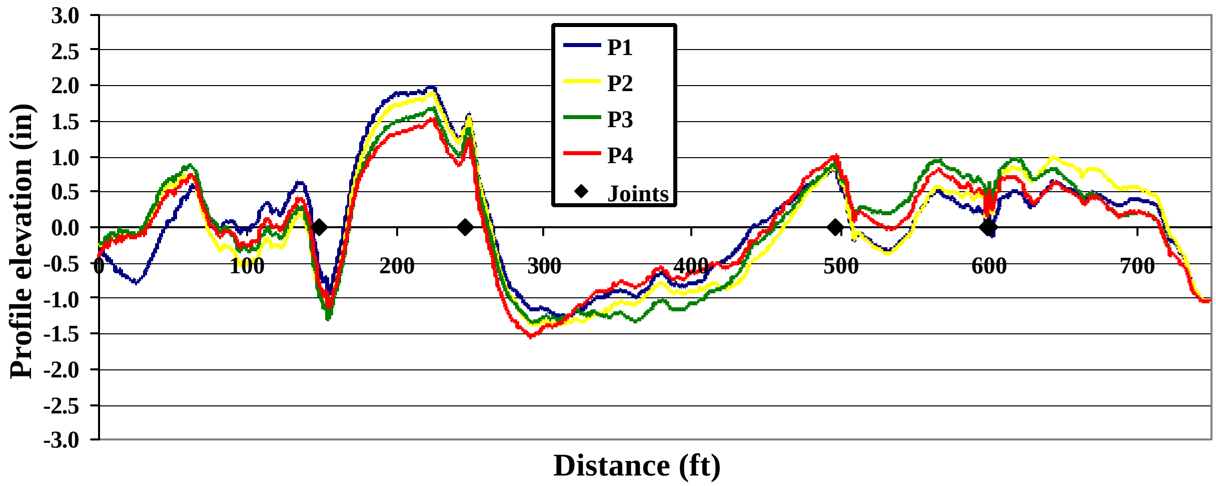

Figure 14. Superposition of the profiles measured using the K. J. Law profiler for testing repeatability at the right wheel path of bridge number 069-0043

Figure 15 illustrates the filtered profile using a moving average for the right wheel path of bridge number 069-0077, while Figure 16 shows the profile for the left wheel path of bridge number 069-0077. Although there is a small difference in profile given by different passes of the equipment, like between 0 and 50 ft (15.4 m) in bridge number 069-0043 (Figure 14), it does not affect IRI and RN greatly. PI, however, has a high variability, as shown in Table 1. Comparing all the profiles for a given bridge and wheel path, it can be concluded that there is good repeatability for all tested profiles.

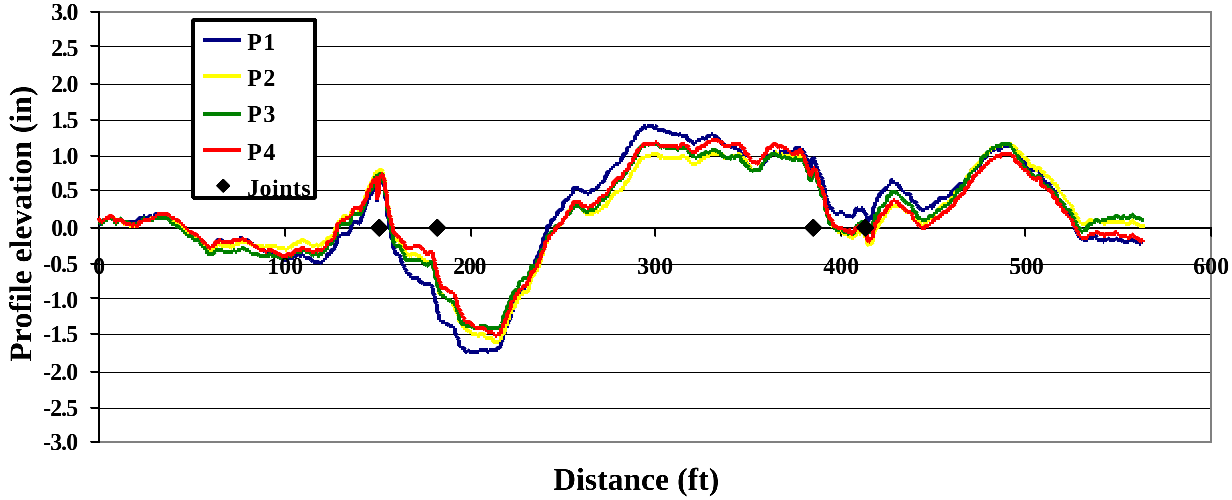

Figure 15. Superposition of the profiles measured using the K. J. Law profiler for testing repeatability at the right wheel path of bridge number 069-0077

It must be emphasized that when using the RoadRuf program to calculate the smoothness index for a profile measured using the K.J. Law profiler, another moving average filter should not be used. If it is used again, the results will show that the pavement is smoother than it actually is, since the profile will be attenuated twice. Just to illustrate the effect of the filter on measuring the profile, a high pass moving average filter was applied to the profile obtained using the K.J. Law profiler. The difference in profile before and after using the filter again is shown in Figure 17 for the right wheel path of bridge number 069-0043, in Figure 18 for the right wheel path of bridge number 069-0077, and in Figure 19 for the left wheel path of bridge number 069-0077. The filter changes the profile significantly.

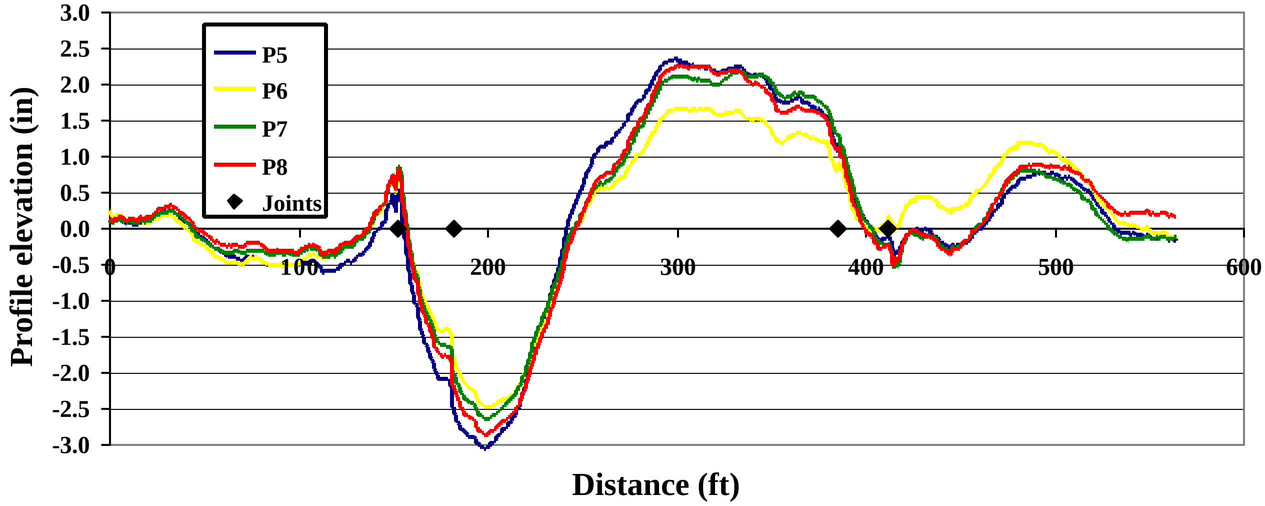

Figure 16. Superposition of the profiles measured using the K. J. Law profiler for testing repeatability at the left wheel path of bridge number 069-0077

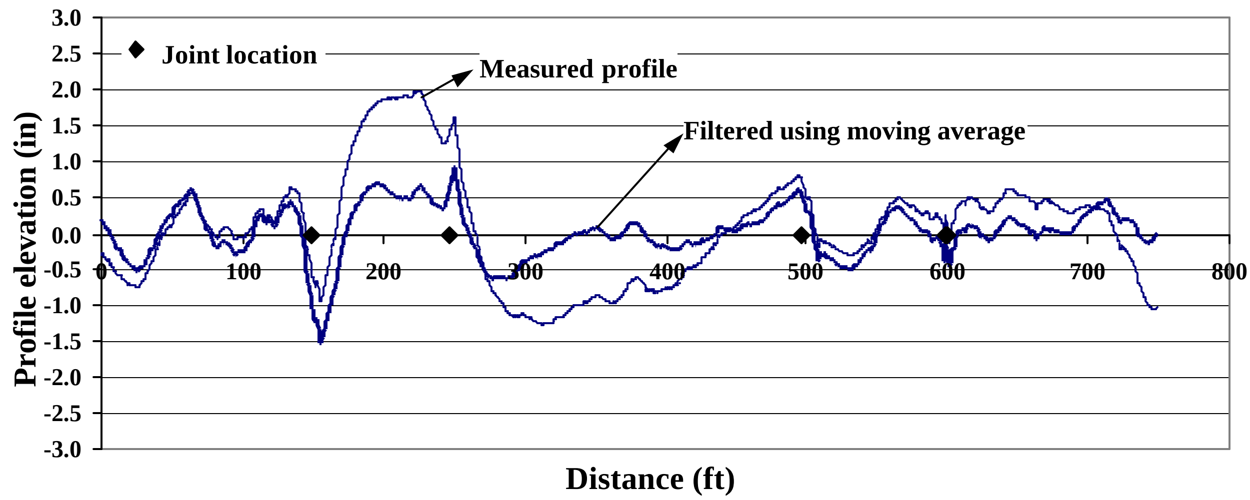

Figure 17. Difference in profile before and after filtering for the first pass at the right wheel path of bridge number 069-0043

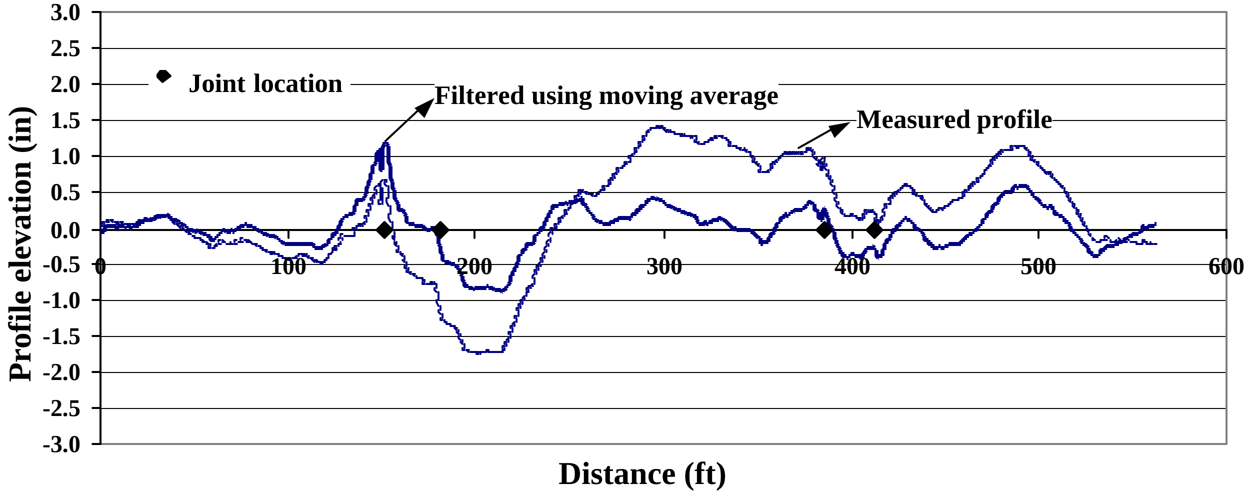

Figure 18. Difference in profile before and after filtering for the first pass at the right wheel path of the bridge number 069-0077

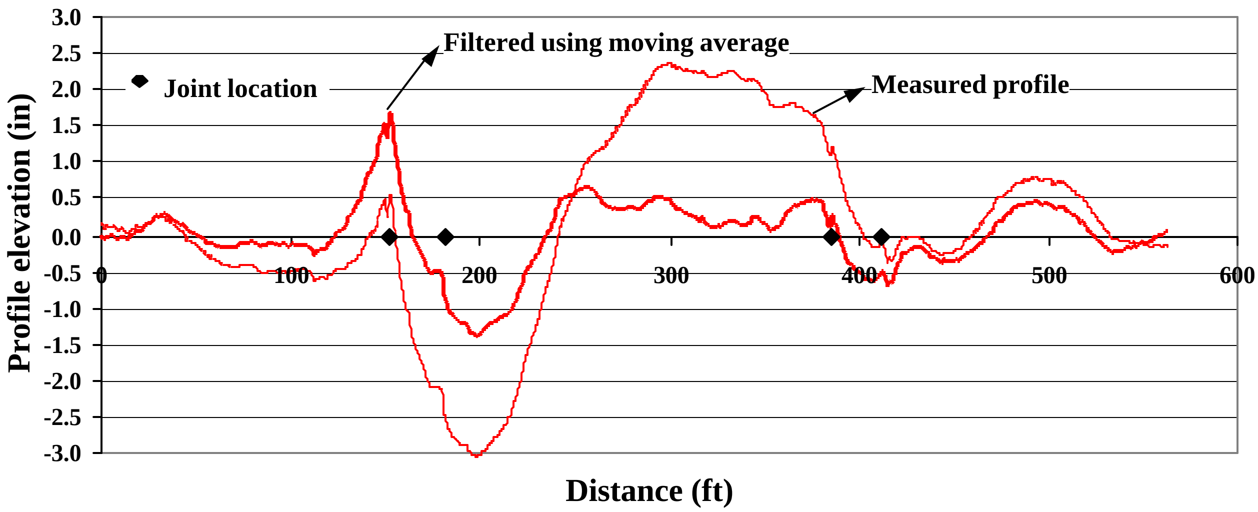

Figure 19. Difference in profile before and after filtering for the first pass at the left wheel path of the bridge number 069-0077

4.3.3 Smoothness Statistics

Two smoothness indices are presented for all of the test sections: IRI and PI. These values were calculated based on the profile measured at certain intervals using a K.J. Law Lightweight profiler. IRI is a mathematical transform of a true profile, while PI is derived from the California profilograph, which is a mechanical filter-based device that does not measure the true profile of the pavement surface. A more detailed discussion of these smoothness indices was presented in Section 2.

IRI was calculated for each wheel path, as shown in Figure 20. These data are summarized in Appendix D, where the data are separated according to the date they were obtained. These results show that IRI values range from 123 to 237 in/mi (1.94 to 3.74 m/km) for the left wheel path and from 131 to 224 in/mi (2.07 to 3.54 m/km) for the right wheel path. By comparison, a new pavement can be constructed as smooth as 40 in/mi (0.63 m/km). A report on Illinois Interstate Surface Quality (IDOT, 1997) showed that in 1996 the average statewide IRI was approximately 100 in/mi (1.58 m/km). In this report, IRI data was broken into four quartiles, each containing 25% of the Illinois Interstate pavement mileage tested. The results, as illustrated in Figure 21, can be summarized as follows: first quartile IRI was between 40 and 73 in/mi (0.63 and 1.15 m/km), second quartile IRI was between 74 and 100 in/mi (1.17 and 1.58 m/km), third quartile IRI was between 101 and 137 in/mi (1.59 and 2.16 m/km), and the fourth quartile has IRI greater than 137 in/mi (2.16 m/km) and smaller than 200 in/mi (3.16 m/km).

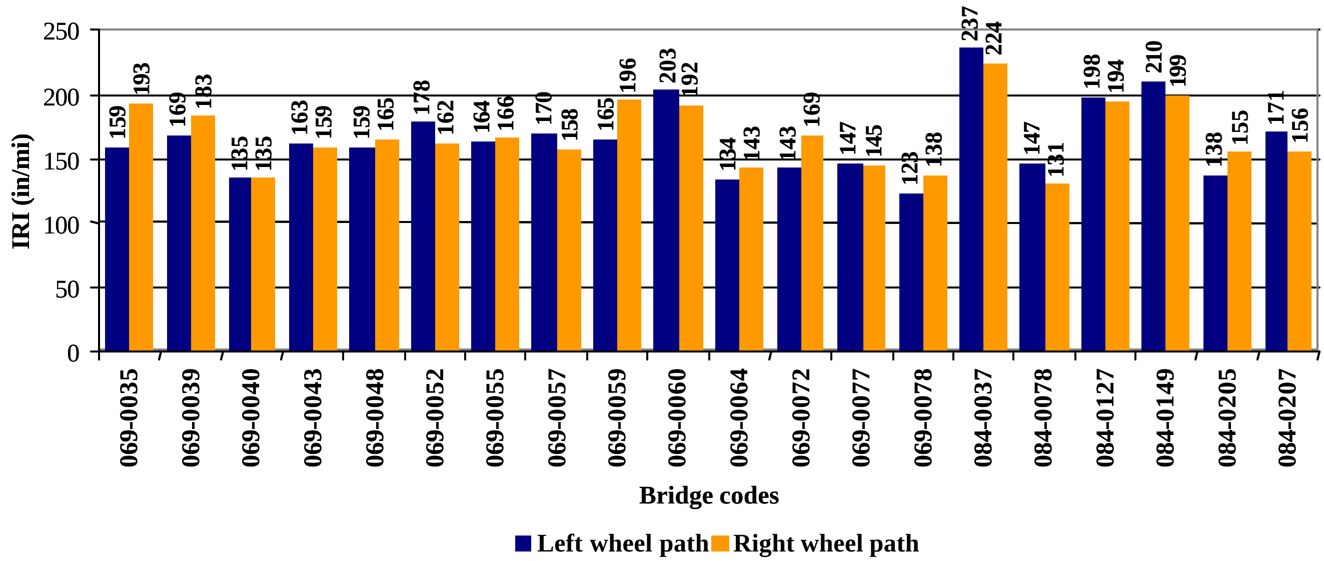

Figure 20. IRI for the left and right wheel paths

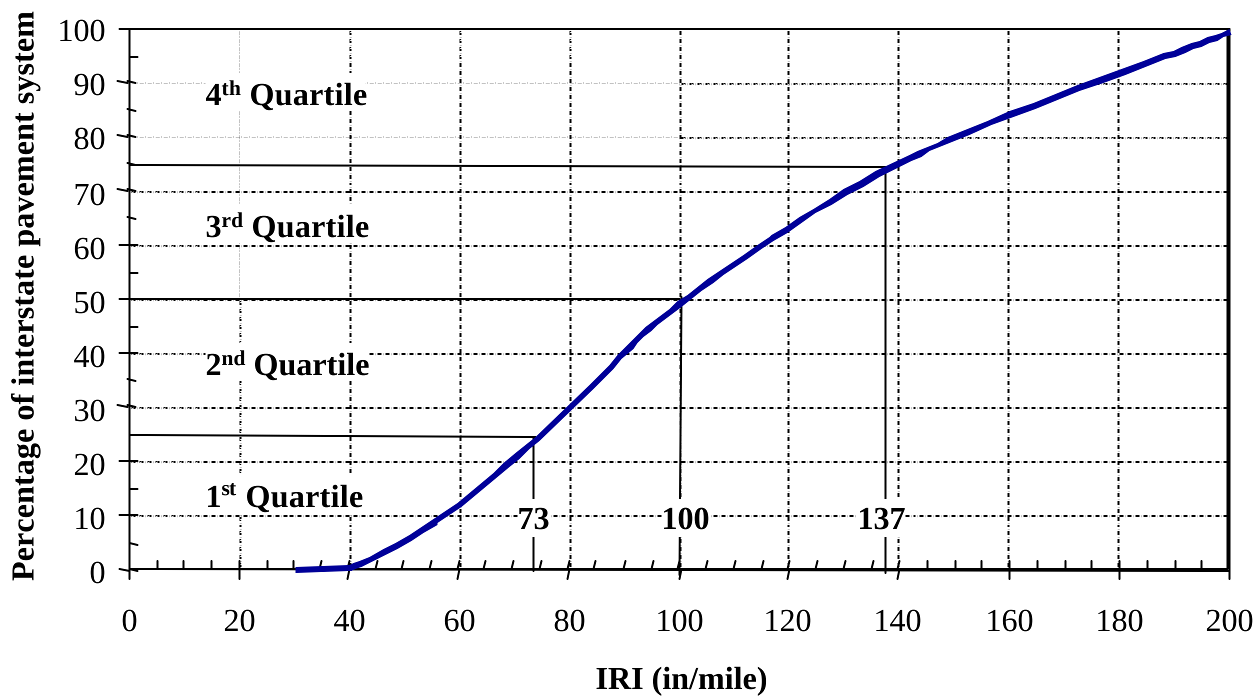

Figure 21. IRI quartile analysis (IDOT, 1997)

Figure 22 shows a histogram of the IRI values for the right wheel path of all 20 bridges that were tested. It is observed that 65% of all tested bridges (13 out of 20) have an IRI between 130 and 170 in/mi (2.05 and 2.68 m/km) and that the rest have an IRI greater than 180 in/mi (2.84 m/km). It is also observed that 25% of all tested bridges have an IRI between 190 and 200 in/mi (3.00 and 3.16 m/km).

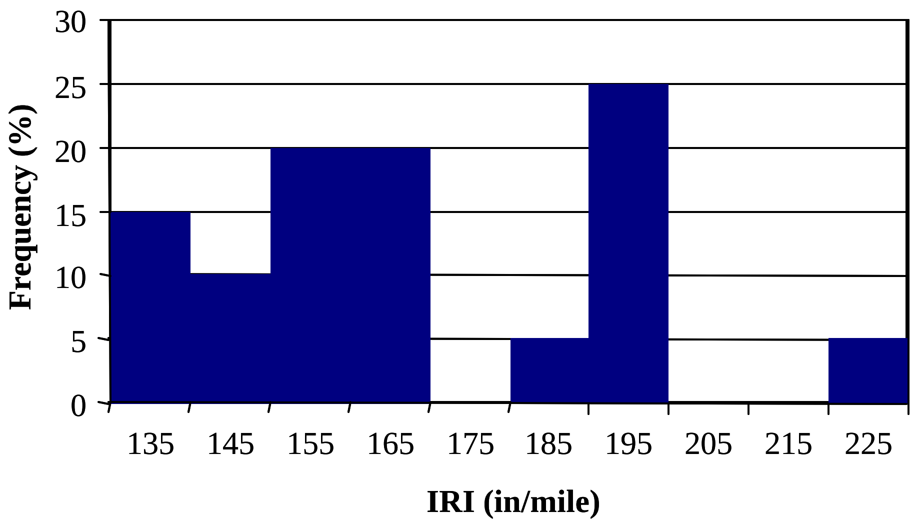

Figure 22. Histogram of IRI values for the right wheel path of the 20 tested bridges

The K.J. Law Lightweight Profiler also provided the PI (0.2-in or 5.1-mm blanking band) for the entire section of all the bridges tested, except for bridge number 069-0064, as illustrated in Appendix D. The data are separated according to the date they were obtained. Figure 23 shows the calculated PI for each wheel path. It is observed that PI values range from 23.5 to 62.1 in/mi (2.54 m/km) for the left wheel path and from 22.7 to 69.5 in/mi (0.36 to 1.10 m/km) for the right wheel path. The ratio between the PI value in the left and right wheel path varies from 0.7 (bridge number 084-0078) to 1.4 (bridge number 069-0072).

In the following analysis, the bridge components will be separated to determine the smoothness of the bridge system (deck and approach pavement evaluated separately from the existing pavements). As discussed before, the existing pavements consist of 150 to 200 ft (45.7 to 61.0 m) of pavement leading up to the first joint in the bridge system and following the last joint. The test sections will be separated into three parts: bridge deck combined with the approach pavements, front existing pavement, and rear existing pavement, as shown in Appendix B. The data analysis of the entire test section clearly shows that IDOT bridges are much rougher than pavements.

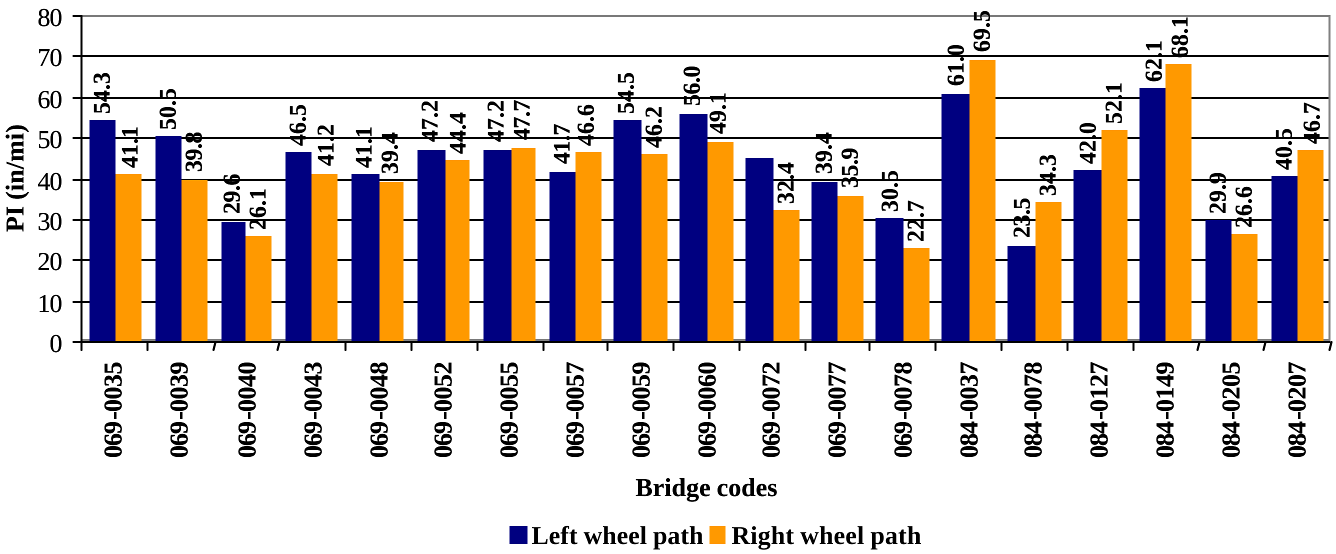

Figure 23. PI (0.2-in blanking band) for the left and right wheel paths

IRI was calculated for the right wheel path of each subsection of the bridge (bridge deck plus approach pavement, and front and rear existing pavements). This analysis was performed using RoadRuf software to calculate IRI for each of the subsections shown in Appendix B. RoadRuf is a free software package developed by the University of

Michigan Transportation Research Institute (UMTRI, 1997) for the Federal Highway Administration.

Figure 24 presents the IRI values obtained for some of the bridges, and Figure 25 shows the rest. These data, along with some statistical parameters, are also shown in Appendix E. It is observed that the IRI for the front existing pavement varies from 69 to 208 in/mi (1.09 to 3.28 m/km). The rear existing pavement presents about the same variation as the front existing pavement, except for the gravel rear existing pavement of bridge number 084-0037 (Hazel Drive), which has an IRI value of 490 in/mi (7.73 m/km). The average IRI for the front existing pavements is 142 in/mi (2.24 m/km), whereas the rear approach pavements have an average IRI of 165 in/mi (2.60 m/km). This analysis also shows that the IRI for the bridge deck plus the approaches varies from 114 to 225 in/mi (1.8 to 3.55 m/km), with an average IRI of 171 in/mi (2.70 m/km).

Comparing the IRI of the bridge deck plus approaches, with the IRI of the existing pavements, it is observed that the bridge deck plus approaches is rougher than both approach pavements in 65% of the bridges. The bridge deck plus approaches is rougher than at least one of the existing pavements in 85% of the bridges. It is also observed that the bridge deck plus approaches is rougher than the front existing pavement in 75% of the bridges tested, and the same result is observed for the rear existing pavements.

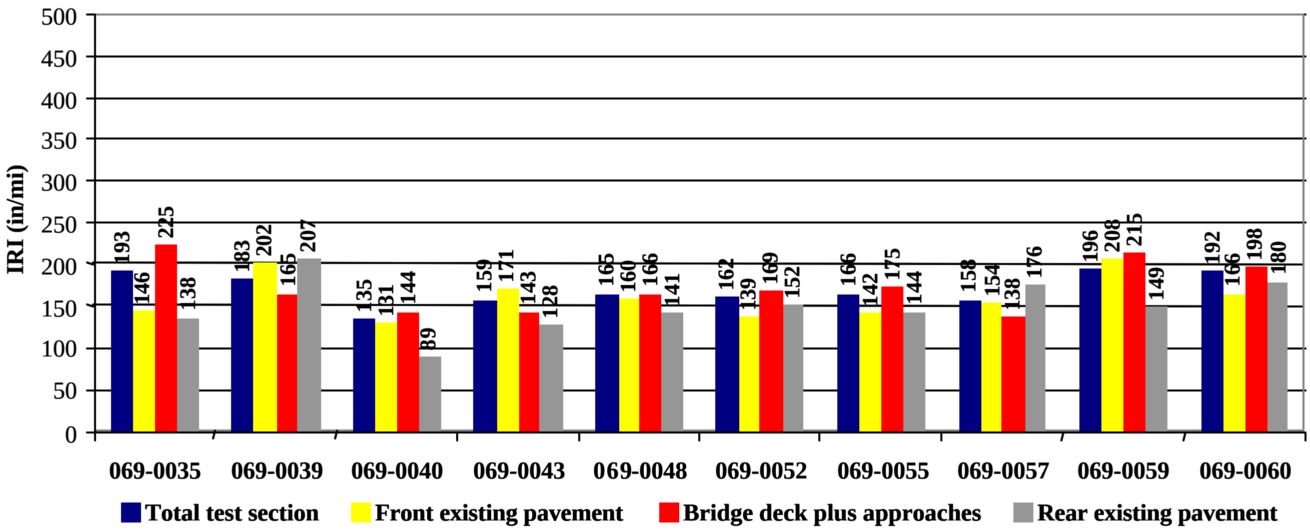

Figure 24. IRI for the right wheel path before and after dividing the bridge into three subsections (bridges 069-0035 to 069-0060)

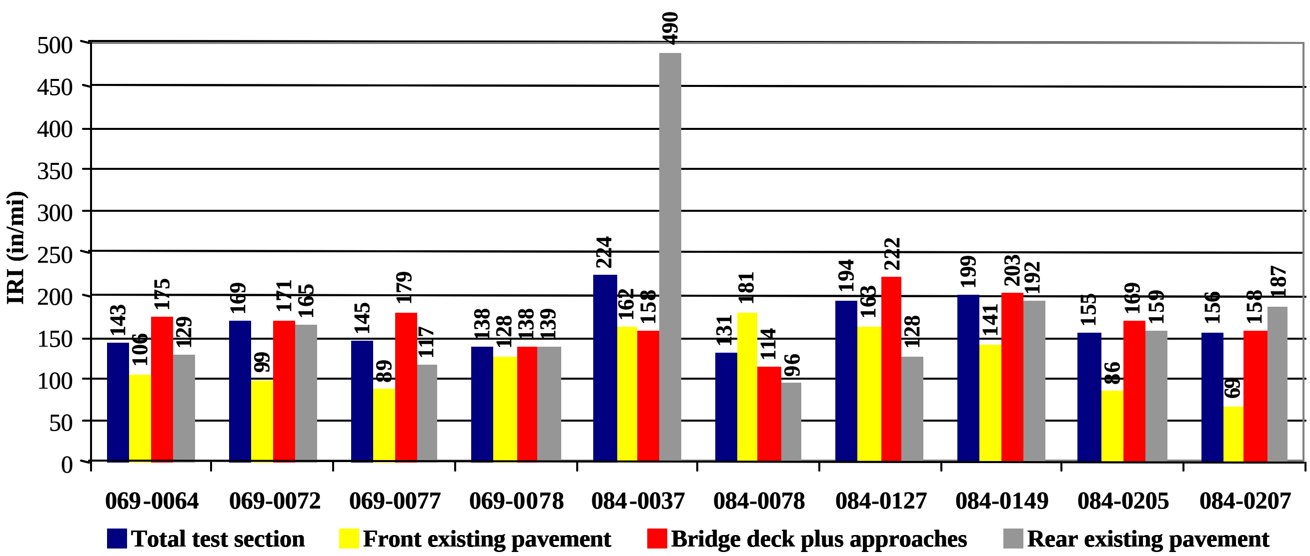

Figure 25. IRI for the right wheel path before and after dividing the bridge into three subsections (bridges 069-0064 to 084-0207)

4.3.4 Profile Analysis

The right wheel path profiles for all 20 bridges tested are shown in Appendix F, along with IRI and RN for total section, front existing pavement, bridge deck, and rear existing pavement. Some information about each bridge is presented, as well as two pictures of each bridge. The trends of the profiles and their implications on the smoothness specifications will be discussed in the following paragraphs.

Approximately 30% of the bridges tested showed an increasing slope starting at the front approach pavement and raising to the bridge deck. About 50% of the profiles showed a sag in the bridge deck, usually starting at the end of the bridge approach pavement. A large spike can be seen at many of the joints. In approximately 80% of the bridges, a large spike can be seen at many of the joints. Some are steep spikes directly over the joint, while others are less steep with the peaks centered over the joint. Each of these aspects will be discussed in detail in the following sections.

Increasing Slope in the Front Approach Pavement

In 6 of the 20 bridges, the bridge profile had an increasing slope starting at the beginning of the front approach pavement, and raising to the beginning of the bridge deck. Many of these peaks are located at the top of the joint between the front approach pavement and the bridge deck, falling when the bridge deck is reached. This mostly occurs in the front approach with a dip at the beginning of the front approach occasionally observed. The profiles of the six bridges are shown in Figure 26.

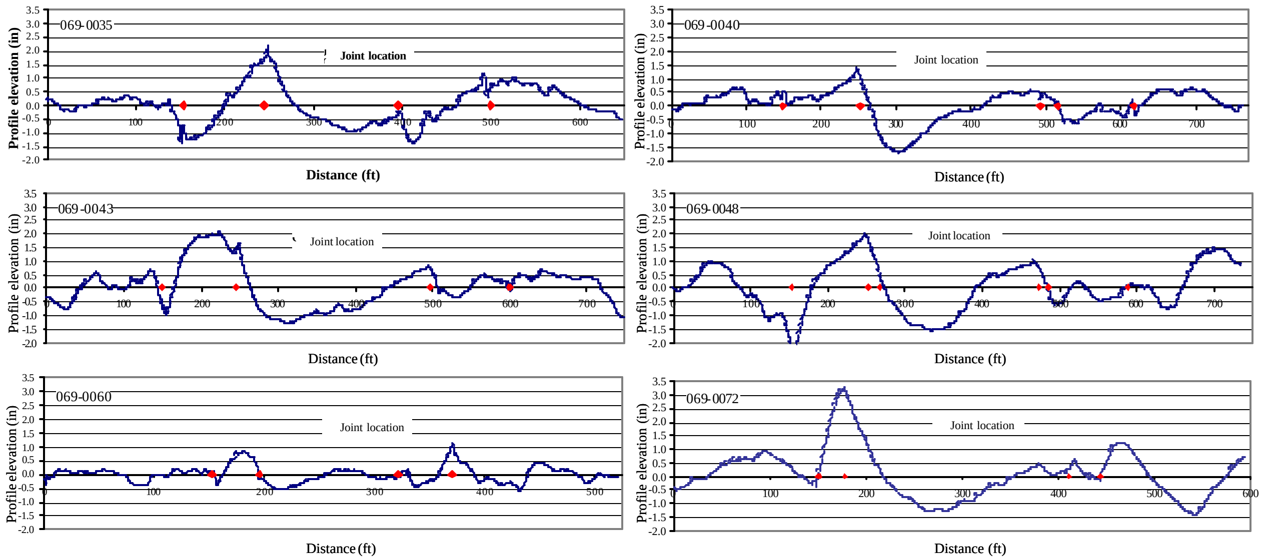

Figure 26. Bridges presenting an increasing slope in the approach slab

Bridge Deck Sagging

A common trend in the profile was a large sag at the beginning of the bridge deck. This was observed in 10 of the 20 bridges, as shown in Figure 27. This sag can also occur at the end of the bridge deck, in or after the rear approach pavement on some bridges. These sags come in several shapes, from sharp dips as in bridge number 069-0060 to smoother shallow dips as in bridge number 069-0072.

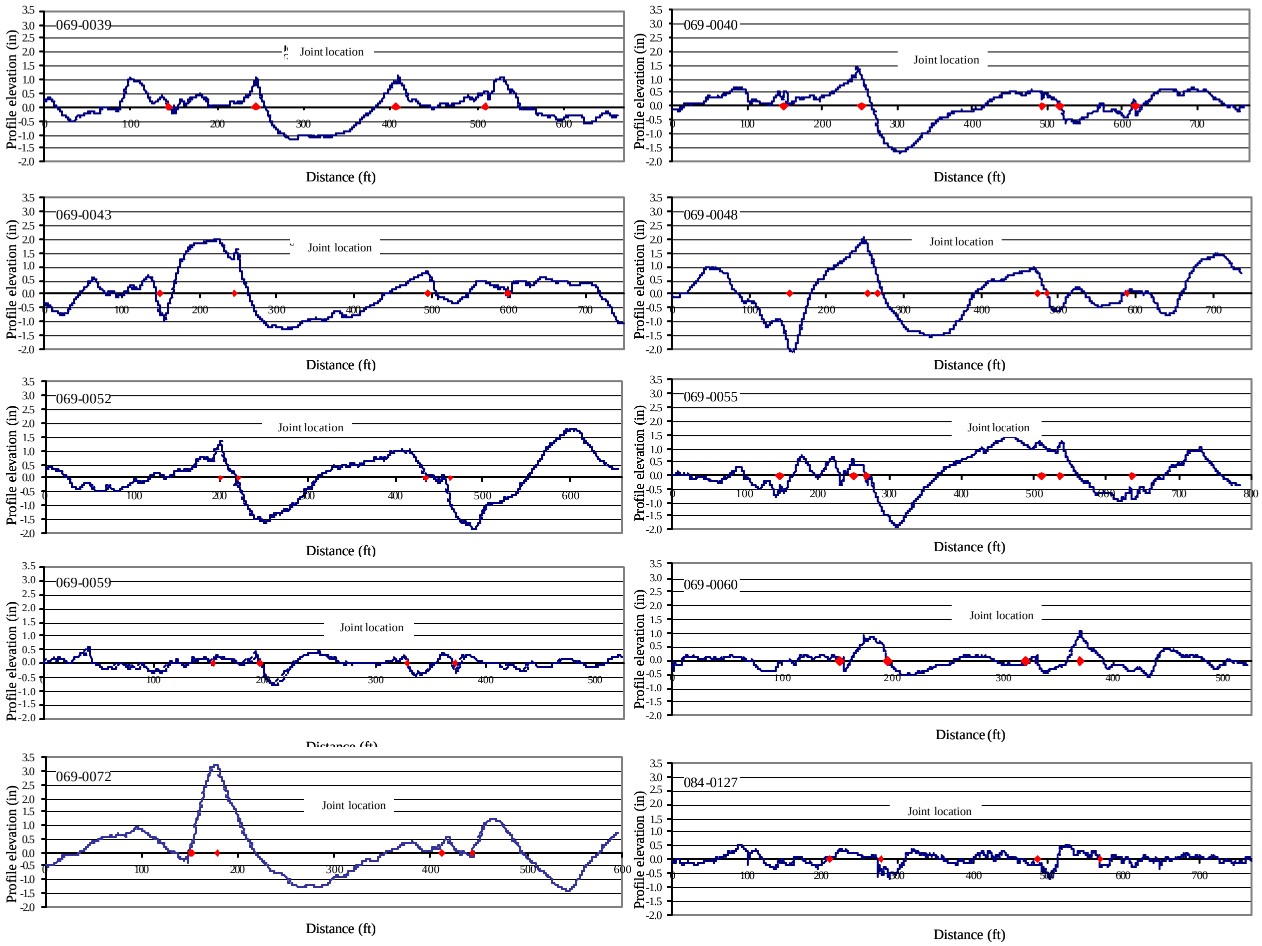

Figure 27. Bridges presenting a sag at the beginning of the bridge deck

Spikes at the Joints

One of the most noticeable trends in the profiles is a large spike occurring at many of the bridge joints. This was observed in 16 of the 20 bridge profiles, as shown in Figure 28. Some spikes are sharp, as in bridge number 069-0039, while others are more gradual, as in bridge number 069-0072. The peaks are centered at a joint in the bridge, usually located between the approach slabs and the bridge deck.

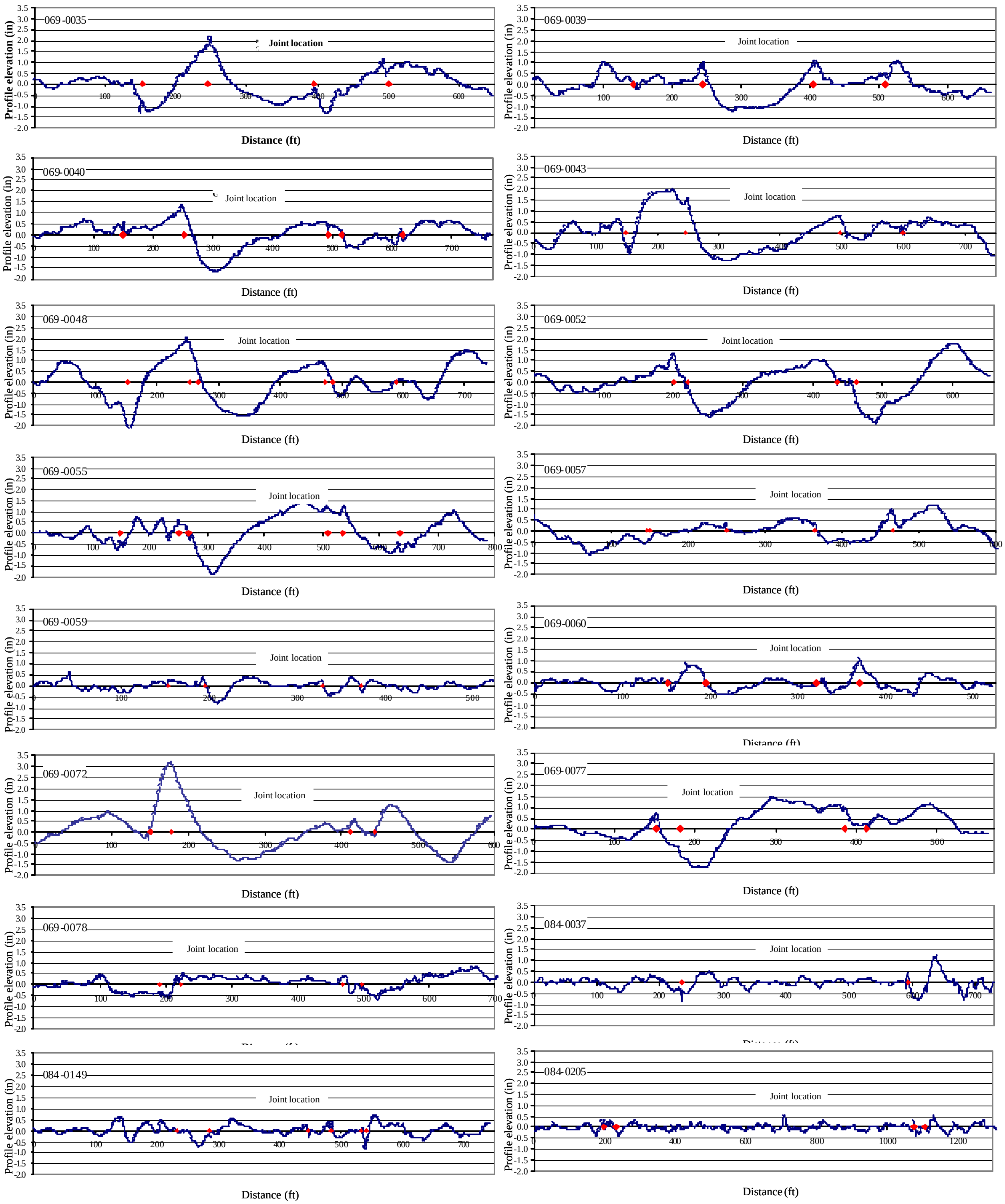

Figure 28. Bridges presenting spikes at some joints

4.3.5 Deck Grinding Simulation

Grinding is a common procedure to improve smoothness in pavements. Hancock (2000) examined the effect of diamond grinding on pavement smoothness. The author concluded that grinding not only reduces roughness but also apparently slows down the rate of roughness progression.

The Georgia DOT uses grinding on newly constructed bridges. In order to see what effect grinding would have on smoothness of the sampled bridges, a grinding analysis was performed. In this analysis the GDOT grinding criteria were applied to the bridge data and the profiles were modified to simulate the effects of grinding. The bridge smoothness was then recalculated using the modified data.

GDOT smoothness specification requires that all bumps over 0.2 in (5.1 mm) be ground to that level. This specification forces contractors to pay more attention to the smoothness during construction for the following two reasons. Firstly, they must do additional work if smoothness levels are not initially met. Secondly, they can receive a bonus incentive for a smoother bridge. A grinding simulation was performed to see what effect the grinding requirement would have on the bridges tested in this study. In the simulation, all of the bumps in the bridge data greater than 0.2 in (5.1 mm) were leveled down to that mark to simulate grinding. This resulted in a modified profile similar to if the bridge was ground down to the GDOT levels. These modified profiles are shown in Appendix G.

The IRI values for the right wheel path before and after the grinding simulation are shown in Figure 29. These IRI values, along with some statistical data, are shown in Appendix H. The IRI before the grinding simulation varies from 131 to 224 in/mi (2.07 to 3.54 m/km), while after the grinding simulation it varies from 81 to 201 in/mi (1.28 to 3.17 m/km). The average IRI dropped from 168 to 127 in/mi (2.65 to 2.00 m/km). It is also observed that the maximum reduction in IRI after the grinding simulation (46%) occurred in bridge number 069-0072, whereas the minimum reduction (4%) occurred in bridge number 084-0078. Figure 30 shows how grinding greatly improved the smoothness characteristics of the bridges. Before grinding, 50% of the right wheel path of the tested bridges had an IRI below 162 in/mi (2.56 m/km), and after grinding, this IRI value dropped to 116 in/mi (1.83 m/km). However, the IRI values are still much higher than Illinois highway pavements. The IRI values for Illinois highways pavements were obtained from a survey performed by IDOT in 1996 (IDOT, 1997).

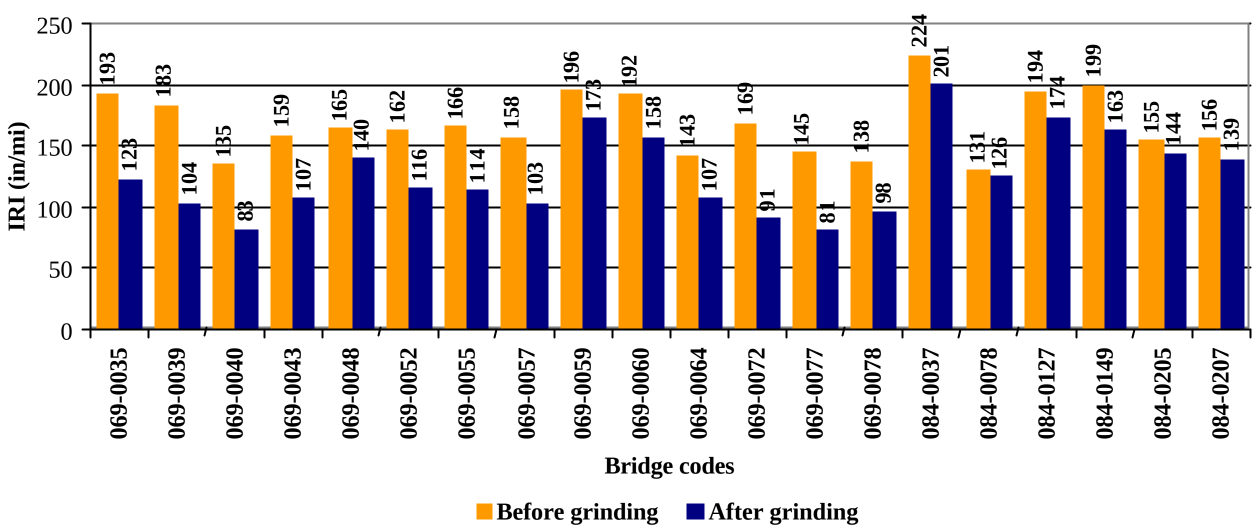

Figure 29. IRI values for the right wheel path before and after grinding simulation

The profiles of bridge number 069-0072 were plotted to analyze the impact of grinding on the IRI value (Figure 31). As expected, this bridge has significant bumps: there is a bump of approximately 3.25 in (82.6 mm) which is reduced to 0.2 in (5.1 mm) when grinding is simulated. The reason that the IRI for the right wheel path value in bridge number 084-0078 changed only 4% after simulating grinding can be explained by analyzing the measured profile before and after simulating grinding for this bridge (Figure 32). It is observed that there are only two bumps with an elevation of only 0.5 in (12.7 mm).

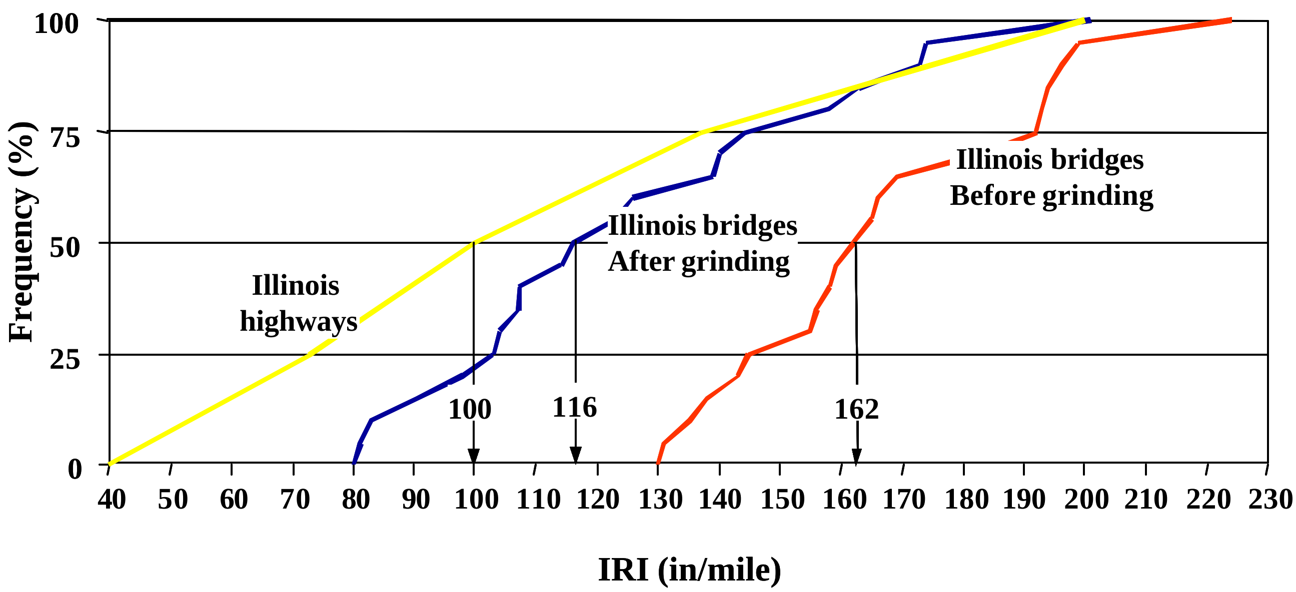

Figure 30. Cumulative frequency distribution of bridge IRI before and after grinding simulation

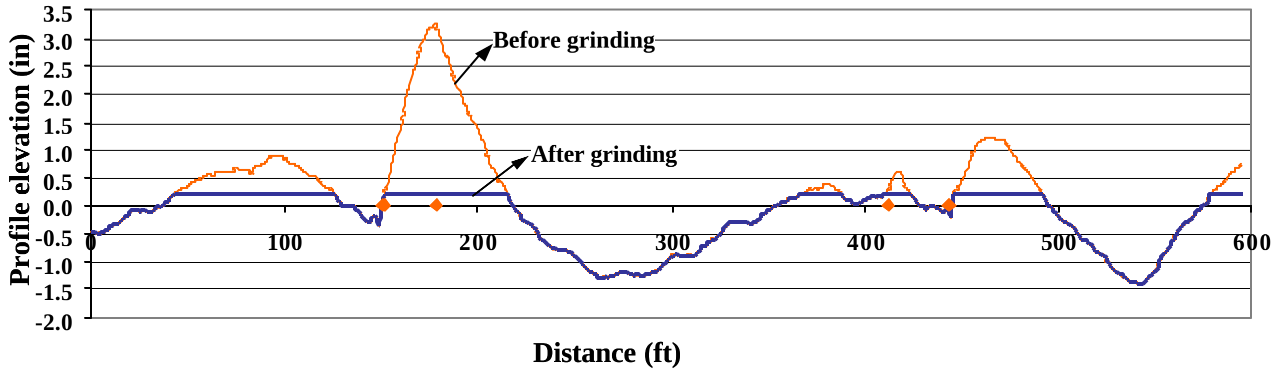

Figure 31. Measured profile before grinding simulation and assumed profile after grinding simulation of bridge number 069-0072

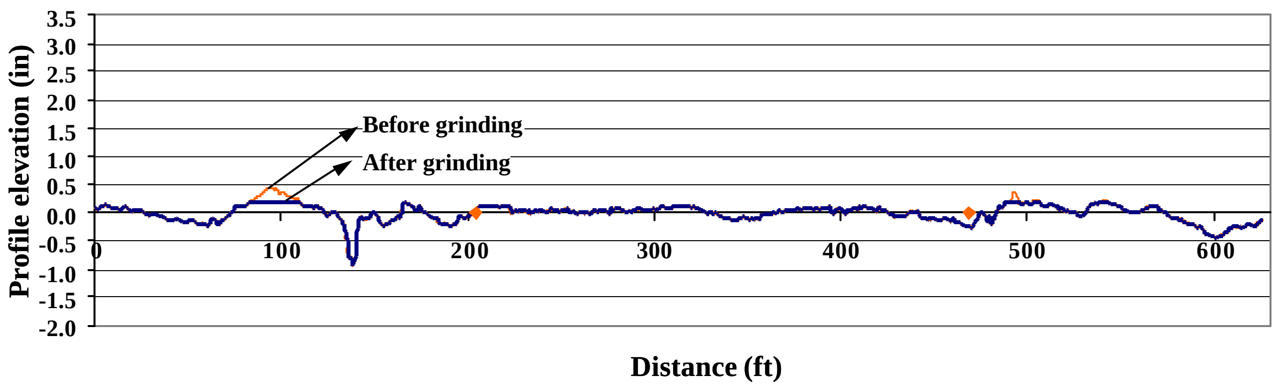

Figure 32. Measured profile before grinding simulation and assumed profile after grinding simulation of bridge number 084-0078

4.3.6 Determination of a Smoothness Index

Practically all of the existing smoothness specifications for new highway pavements are based on the PI. There exist just a few smoothness specifications for bridges, and all are based on the PI. Therefore, it is important to convert the available specification limiting values to IRI, in order to develop a general understanding of a rating system based on IRI.

The American Concrete Pavement Association (ACPA) has been compiling a database since 1998 from surveys of state highway departments. This database can be accessed through the Internet (ACPA, 2000). The smoothness specification is divided into measuring equipment and smoothness index, pay factor and limits, blanking band and must-grind bump, and incentive/disincentive. This survey is shown in Appendix I. Figure 33 shows the measuring equipment used in all US states according to this survey. It is observed that about 70% of the smoothness specifications in the US use the California profilograph and only 2% use a non-contact profiler.

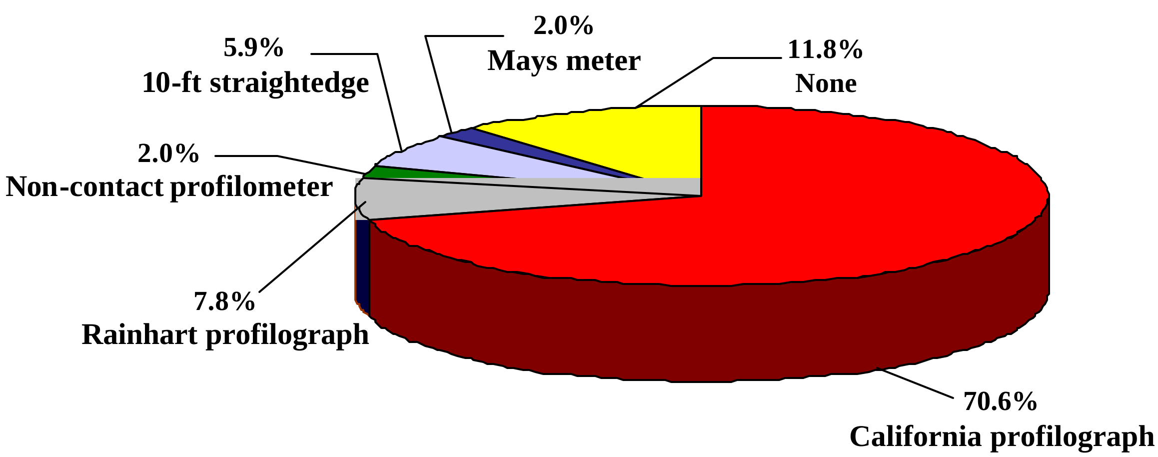

Figure 33. Distribution of measuring equipment used in pavement smoothness specifications in the US among all states (source: ACPA, 2000)

Figure 34 shows the smoothness indices used by the various states. About 70% of the states use the PI, and only 6% use IRI as a smoothness index. As 78.4% use a profilograph, it was expected that 78.4% of the states would also use the PI. It is also shown that about 20% of the states do not use a smoothness index (they may use a simple rolling straight edge). Figure 35 shows that among the 36 states that use PI as a smoothness index, 72.2% use the 0.2-in (5.1-mm) blanking band and only one state (Washington) uses the 0.3-in (7.6-mm) blanking band. Four states (Kansas, Missouri, Pennsylvania, and South Dakota) use the null-blanking band.

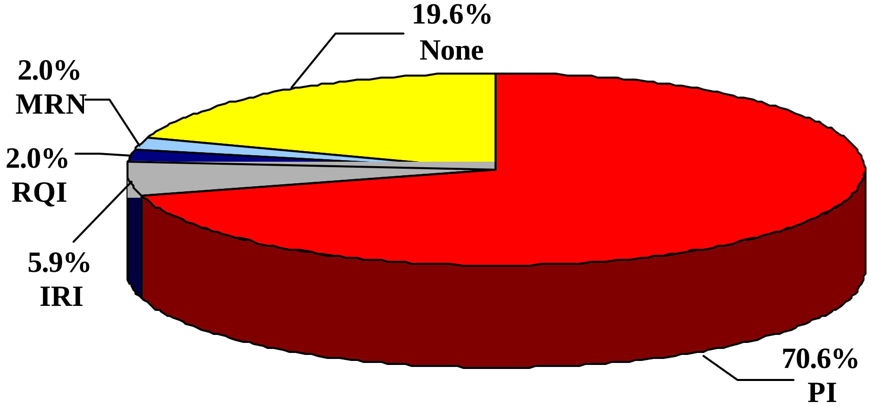

Figure 34. Distribution of smoothness index used in pavement smoothness specifications in the US among all states (source: ACPA, 2000)

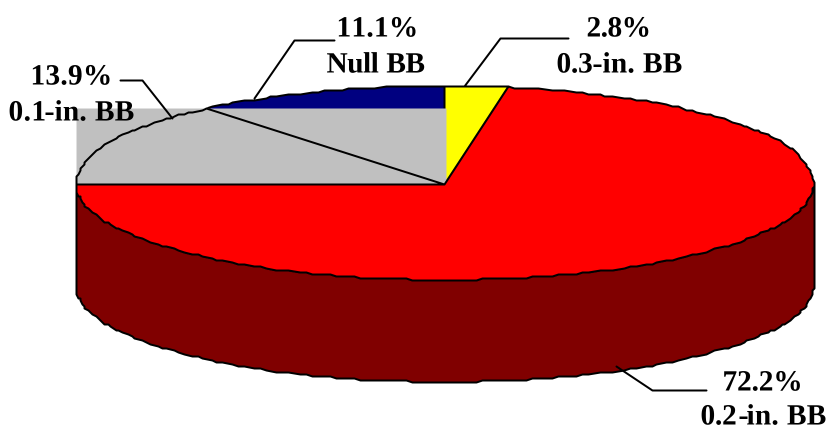

Figure 35. Distribution of blanking band width used in pavement smoothness specifications in the US among the states that use PI (source: ACPA, 2000)

Figure 36 shows that about 60% of the states in the US at least have an incentive or disincentive program. Appendix I also shows some additional information concerning smoothness specifications in the US, such as the must-grind requirement and the pay factors and limits. Also, some measurement requirements are presented, including the profile measurement location, the length of the section evaluated, how the profile index is calculated (hand, computer), and the acceptance measurement (state, contractor).

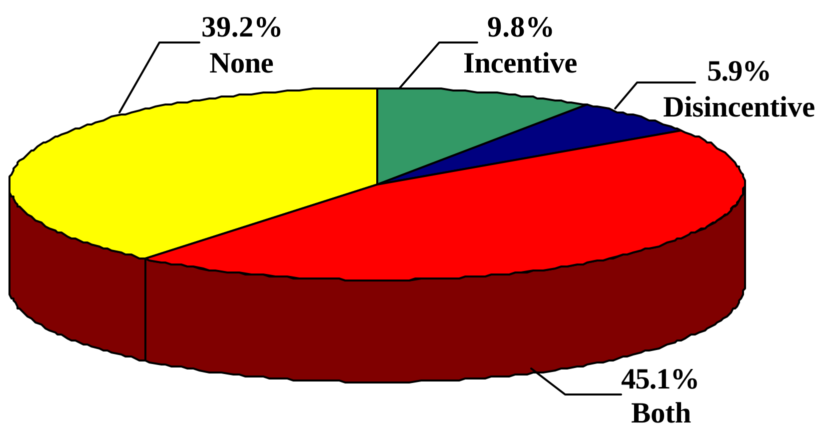

Figure 36. Distribution of incentive/disincentive program for ride quality in the US considering all states (source: ACPA, 2000)

Figure 37 shows some pavement smoothness specifications in the US based on PI values obtained using the 0.2-in (5.1-mm) blanking band. This figure illustrates the PI value to obtain the maximum pay factor, the PI to obtain the minimum pay factor, and the PI range to obtain the full pay factor (100%). It must be emphasized that some states (such as Indiana) do not have an incentive program, while others (like Montana) do not have either an incentive or disincentive program. Indiana has a minimum acceptable value for IRI, but there is no pay factor greater than 100% if a value less than a certain number is obtained. On the other hand, Montana accepts a range of PI values, but the contractor is paid a maximum pay factor of 100%. Actually, their specification could only limit the PI at 15 in/mi (0.24 m/km). The use of a range from 10 to 15 in/mi (0.16 to 0.24 m/km) is not necessary, since there is no incentive program.

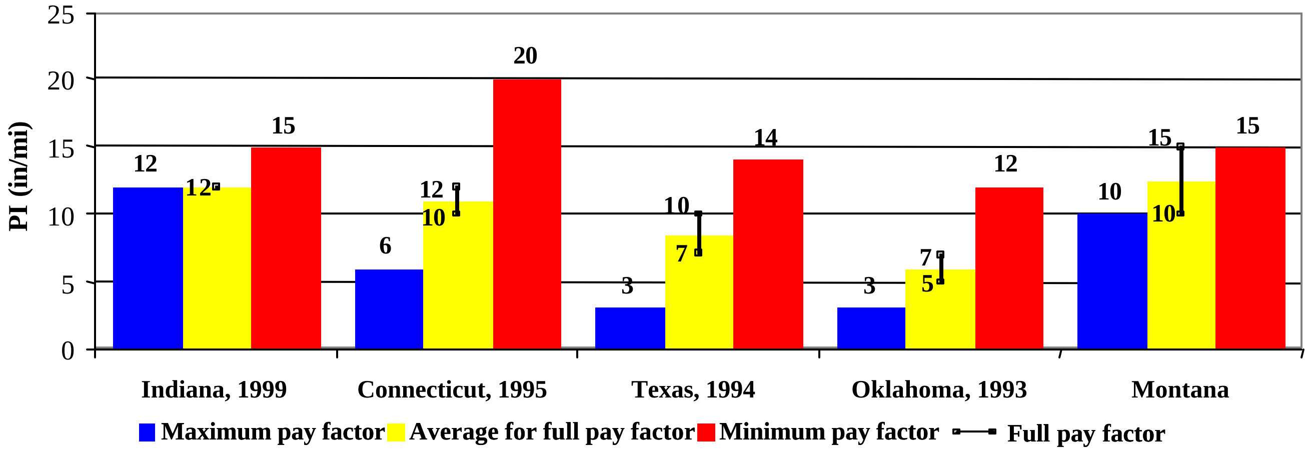

Figure 37. PI (0.2-in or 5.1-mm blanking band) limits of highway pavement smoothness specifications in the US

Kansas also uses the PI determined using the California-type profilograph, but the null blanking band is used instead. Parcells and Hossain (1994) reported the Kansas experience in developing a smoothness specification for PCC, whereas a different publication shows the same experience with asphalt pavement (Hossain and Parcells, 1995). The 0.2-in (5.1-mm) blanking band was adopted for concrete and asphalt pavements, respectively, in 1985 and 1990. However, problems have been reported with pavement profiles with short wavelength and small amplitude, leading Kansas DOT to eliminate the blanking band width. Since this change, smoother pavements have been constructed in Kansas.

Figure 37 suggests that a PI of 12 in/mi (0.19 m/km) obtained with the 0.2-in (5.1-mm) blanking band is acceptable for all the analyzed pavement smoothness specifications. This value does not provide a full pay factor for all specifications, but at least it does not require any corrective action. Using this value of PI, correlation with IRI was analyzed in order to evaluate the level of IRI expected for new projects. A literature survey was performed to identify a correlation between IRI and PI. Fernando (2000) proposed a hyperbolic model, and the NCHRP 1-31 report (Smith et al., 1997) presented several others. ERES Consultants also obtained a correlation between PI (0.2-in or 5.1-mm blanking band) and IRI based on approximately 4500 Long Term Pavement Performance (LTPP) data points (Hoerner et al., 2000). This correlation is referred herein as LTPP.

After analyzing the existing correlation, LTPP was chosen to convert IRI into PI (0.2-in or 5.1-mm blanking band) since it is based on a very comprehensive database. The LTPP model is presented in Figure 38. This figure also shows the conversion from PI to IRI using the Oklahoma PI range. For a pay factor of 100% (PI between 7 and 12 in/mi or 0.11 and 0.19 m/km), IRI varies between 94 and 107 in/mi (1.48 and 1.69 m/km). Pennsylvania is changing its pavement smoothness specification to IRI, and the IRI for a payment of 100% is between 81.4 and 95.0 in/mi (1.28 and 1.5 m/km). Therefore, the upper limit of the Pennsylvania specification for a payment of 100% is about the same as the lower limit using, the LTPP correlation to convert the Oklahoma specification into IRI.

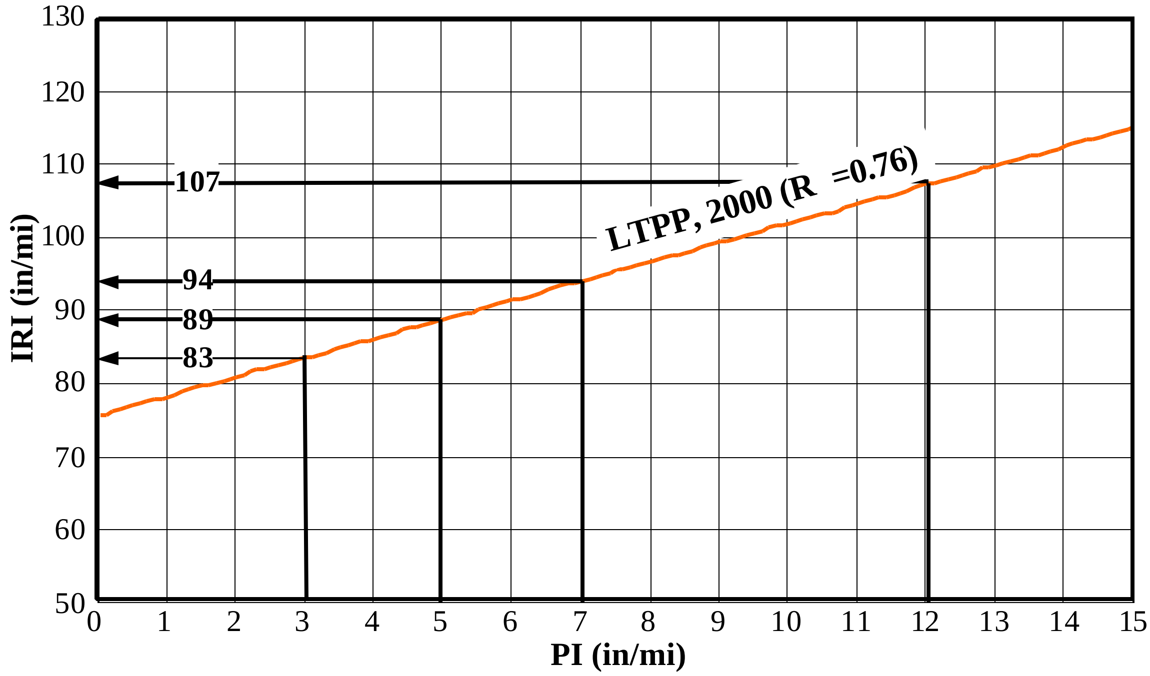

Figure 38. Estimation of IRI values for new highway pavement smoothness specification based on correlation between IRI and PI obtained with the 0.2-in (5.1-mm) blanking band and Oklahoma smoothness specification

Figure 39 compares some smoothness specifications for bridges in the US. Among these specifications, only Kansas is based on the null blanking band. Nebraska and Oklahoma use the 0.2-in (5.1-mm) blanking band. In Kansas, the contractor can have a pay factor of 100%, even if the PI is 50 in/mi (0.79 m/km). However, the contractor has to grind back to 35 in/mi (0.55 m/km) or less. If the PI is greater than 50 in/mi (0.79 m/km), the contractor only gets 95%. Nebraska does not have an incentive program, since the minimum and maximum pay factor is 100%. The maximum PI accepted in Nebraska is 27 in/mi (0.43 m/km). If the PI is greater than this, corrective actions must be taken to reduce the PI to the acceptable value. In contrast, in Oklahoma a pay factor less than 100% is paid if the PI measured with the 0.2-in (5.1-mm) blanking band is 35 in/mi

(0.55 m/km), but no corrective actions are required. The Kansas specification cannot be directly compared to the other two, since it is based on the null blanking band.

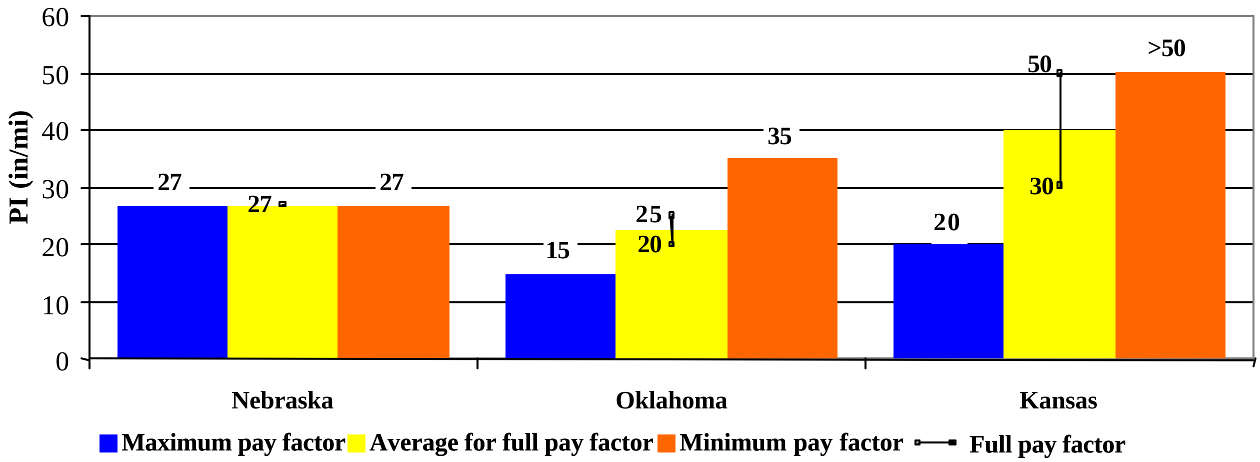

Figure 39. Bridge smoothness specifications in the US Nebraska and Oklahoma based on PI using the 0.2-in (5.1-mm) blanking band; Kansas based on PI using the null blanking band

To compare Kansas and Oklahoma bridge smoothness specifications, it is important to point out that, for a given condition, PI obtained with the null blanking band is much greater than the PI obtained with the 0.2-in (5.1-mm) blanking band. This is due to the fact that the 0.2-in (5.1-mm) blanking band omits some irregularities that are computed when the null blanking band is used. If a PI of 35 in/mi (0.55 m/km) is measured in Oklahoma, no corrective action is needed but a pay factor less than 100% will be paid. In contrast, Kansas accepts a PI of at most 35 in/mi (0.55 m/km). Kansas has much more stringent bridge smoothness requirements, since the allowable PI obtained with the null blanking band is about the same as the allowable PI obtained with the 0.2-in blanking band, although for this level of PI, a pay factor less than 100% is paid in Oklahoma.

Fernando (2000) presented a correlation between IRI and PI for the 0.2-in (5.1-mm) blanking band, and for the null blanking band. The highest value of PI used to develop the correlation between PI obtained with the 0.2-in (5.1-mm) blanking band and IRI was about 15 in/mi (0.24 m/km), whereas the highest value of PI obtained with the null blanking band was 35 in/mi (0.55 m/km). Most of the existing correlations between IRI and PI (0.2-in or 5.1-mm blanking band) were developed for highway pavements, where the level of roughness is much less than in bridges. Only the LTPP correlation (Hoerner et al., 2000) was based on a wide range of roughness. Comparing the existing specifications for bridges and pavements based on PI computed with the 0.2-in (5.1-mm) blanking band, it is observed that the allowable PI for bridges (35 in/mi or 0.55 m/km) is about three times higher than the allowable PI for new pavements (12 in/mi or 0.19 m/km). The PI (0.2-in or 5.1-mm blanking band) at bridges is much higher than the maximum level of roughness used to develop correlation with IRI. Therefore, only the LTPP correlation can be used to convert PI into IRI for bridges, as it is the only correlation based on a wide range of roughness. To compare the LTPP correlation between IRI and PI (0.2-in or 5.1-mm blanking band), a new correlation was developed using the bridge data.

The data used to develop a new correlation between IRI and PI are shown in Appendix J, and the equation obtained from this correlation is shown in Figure 40. Two data points were excluded in this analysis. These two points are the two highest values of IRI (350 and 375 in/mi or 5.52 and 5.92 m/km) obtained between approximately 500 and 700 ft (152.4 and 213.4 m) of the test section of bridge number 084-0037. This correlation is plotted in Figure 41, along with a correlation developed by ERES Consultants using LTPP data (Hoerner et al., 2000). The IDOT correlation provides smaller IRI values for a given PI than the LTPP correlation.

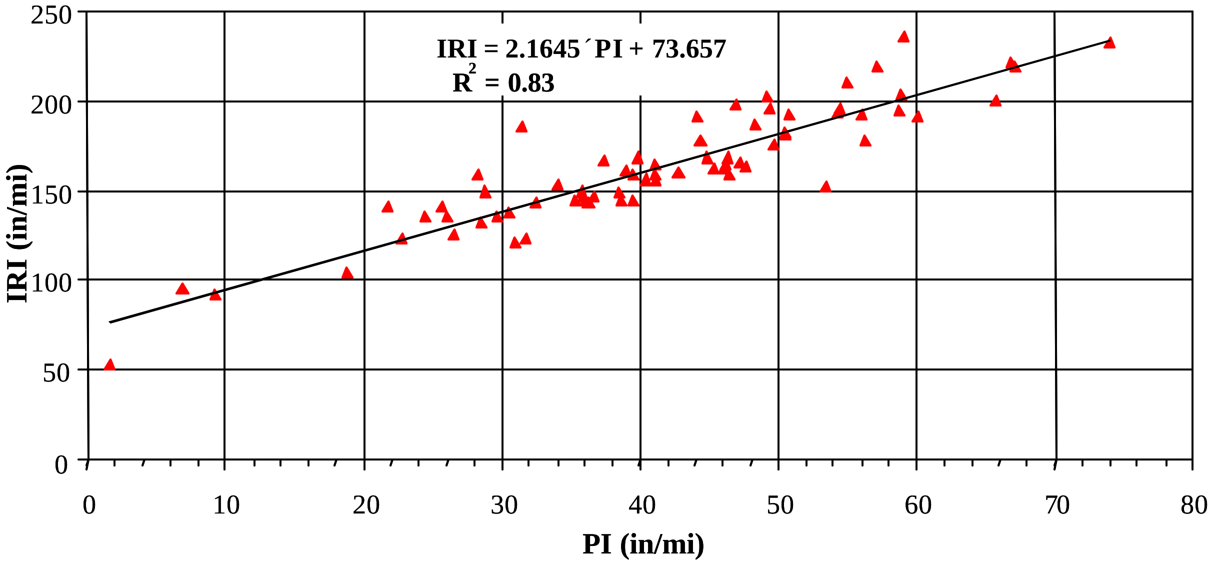

Figure 40. Correlation between IRI and PI using IDOT bridge measurements

The IDOT correlation obtained from bridges was used to convert PI ranges of an existing bridge smoothness specification (Oklahoma). This conversion is shown in Figure 41. The maximum allowable IRI would be 150 in/mi (2.37 m/km), which corresponds to a PI of 35 in/mi (0.55 m/km). This IRI value is approximately the average (148 in/mi or 2.34 m/km) between the average IRI before grinding (168 in/mi or 2.65 m/km) and the average IRI after grinding (127 in/mi or 2.00 m/km) on the selected 20 bridges. On the other hand, the maximum incentive would be given when the IRI is 110 in/mi (1.74 m/km) or less, which corresponds to a PI of 15 in/mi (0.24 m/km).

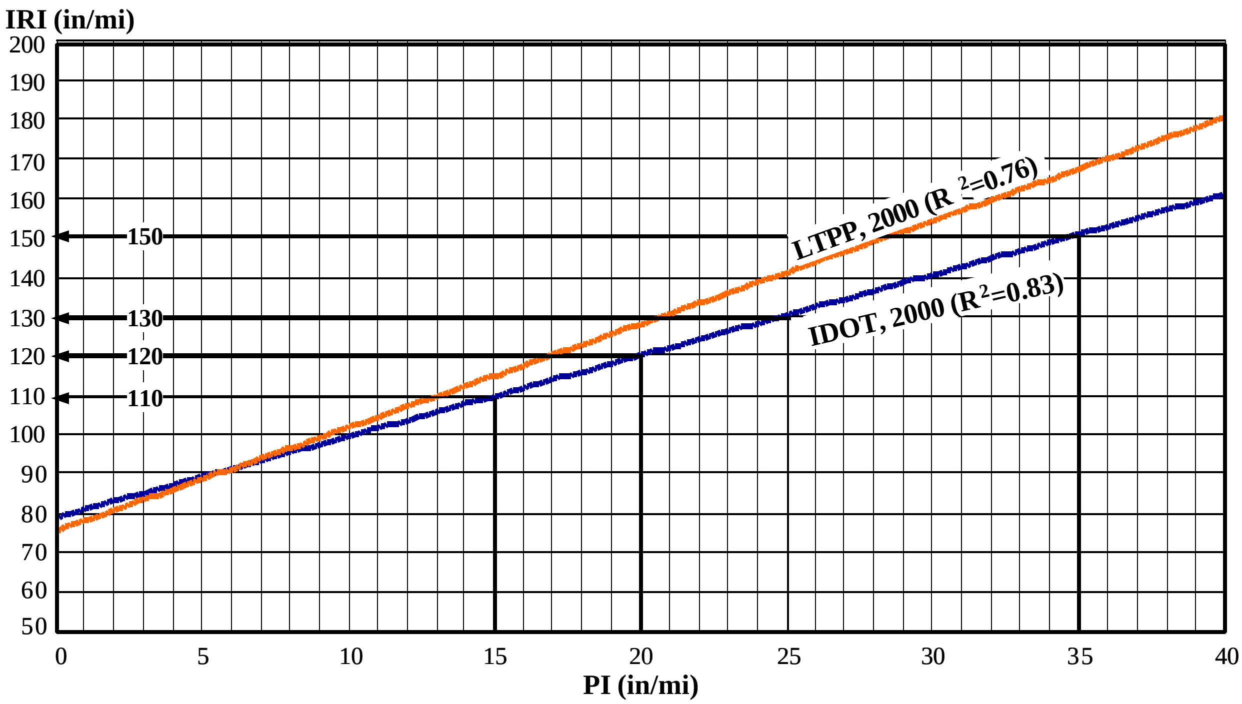

Figure 41. Use of correlation between IRI and PI (0.2-in or 5.1-mm blanking band) to convert Oklahoma specification limits into IRI

It is also important to convert one specification based on the null blanking band, such as Kansas, into IRI values. In order to do that, it is necessary to use the correlation presented in the literature, since only the PI based on the 0.2-in (5.1-mm) blanking band was calculated for the bridge data. ERES Consultants also developed a correlation between IRI and PI based on the null blanking band using LTPP data (Hoerner et al., 2000). Figure 42 shows the LTPP data correlation and one linear correlation proposed by Fernando (2000). The Fernando correlation leads to a smaller IRI value than the LTPP correlation for a given PI value. LTPP was chosen to convert the Kansas PI values into IRI values, since it is based on a huge amount of data (about 4500 points). The Kansas PI limits are shown in Figure 39. It is observed that a pay factor of 100% is given if the PI is between 30 and 50 in/mi (0.47 and 0.79 m/km), which correspond to IRI's between 93 and 137 in/mi (1.47 and 2.16 m/km), respectively. However, the contractor has to grind back to 35 in/mi (0.55 m/km), which is equivalent to an IRI of 104 in/mi (1.64 m/km), according to the LTPP correlation. The maximum incentive is paid when the PI is at most 20 in/mi (0.32 m/km), which corresponds to an IRI of 70 in/mi (1.10 m/km).

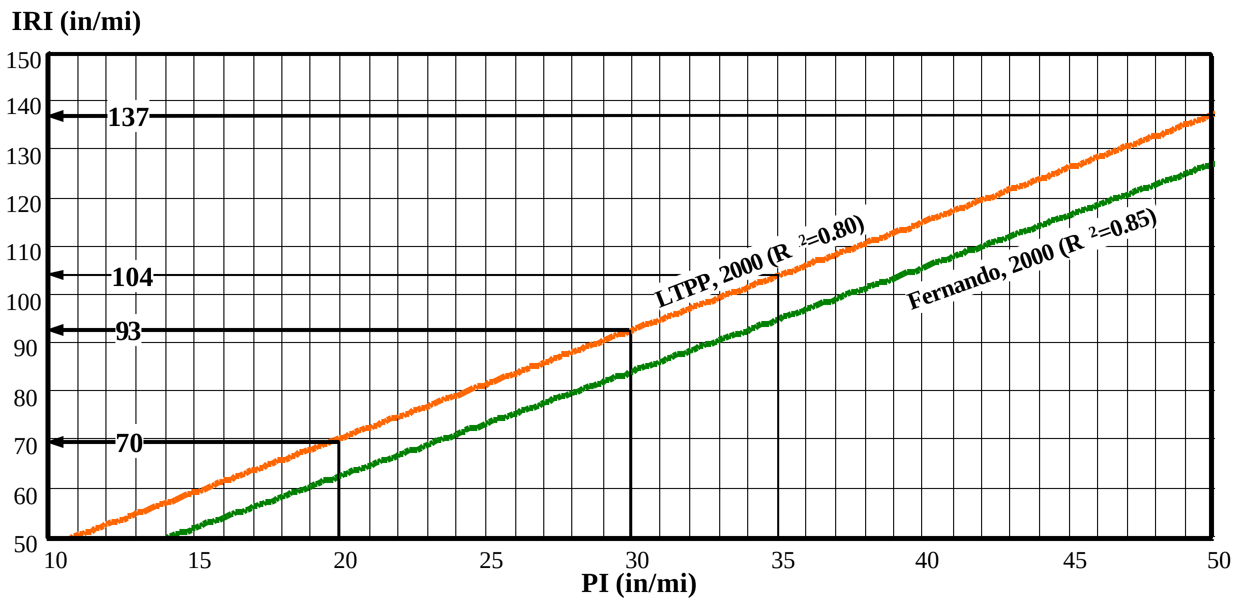

Figure 42. Use of correlation between IRI and PI (null blanking band) to convert Kansas specification limits into IRI

Appendix E shows that the minimum IRI value for the bridge system tested (bridge deck plus approach pavement) is 114 in/mi (1.80 m/km) and that the average IRI for all bridges tested is 171 in/mi (2.70 m/km). After analyzing the predicted IRI limits based on Oklahoma and Kansas bridge specifications, the IRI limits shown in Figure 43 are proposed for the initial Illinois bridge specification. This figure also shows the IRI limits obtained by conversion of PI limits of the Oklahoma highway specification, as well as the IRI limits used by Pennsylvania DOT in their new smoothness specification. It is observed that IRI limits for bridges are higher than for highways. Penn DOT is using lower IRI limit values than those obtained by the correlation with PI (0.2-in or 5.1-mm blanking band) for the Oklahoma specification. It is important to emphasize that the IRI limits proposed for the IDOT bridge smoothness specification must be adjusted after testing additional new bridges. These limits are just a first trial. There is not an IRI-based bridge smoothness specification in the US. Therefore, the specification under development is a unique effort to control bridge smoothness. Grinding the bridge deck to achieve smoother ride may be required in many cases.

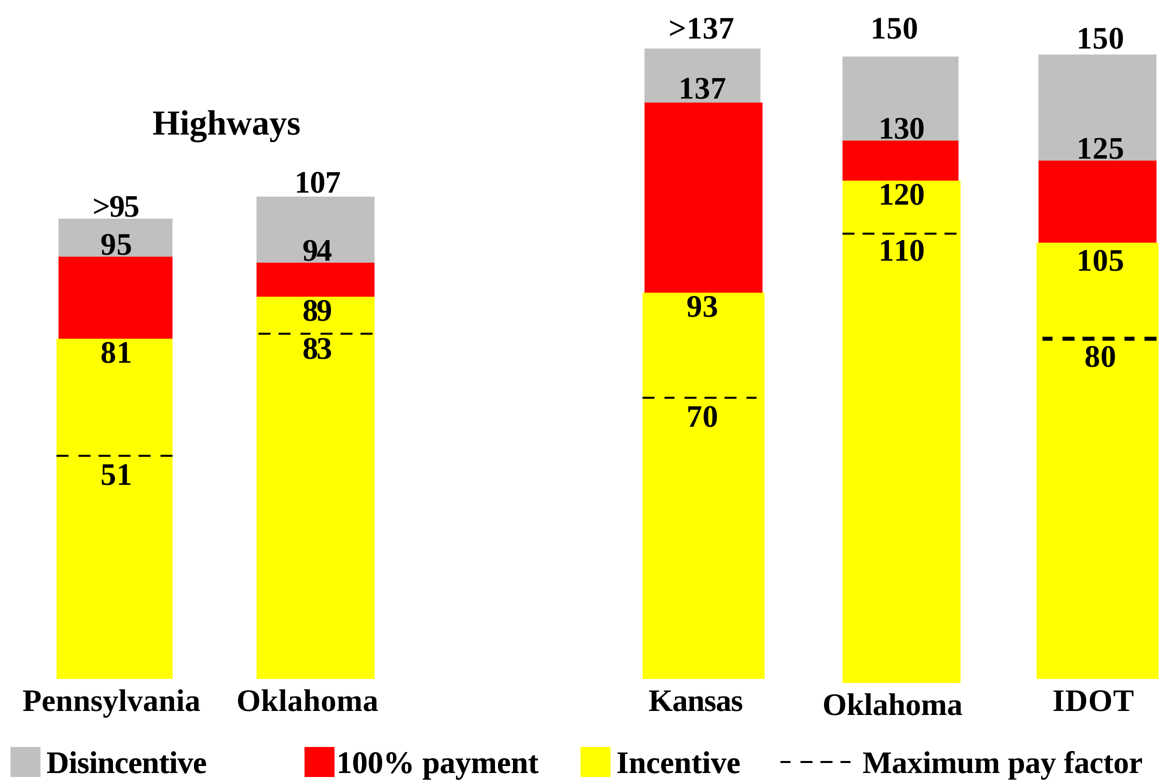

Figure 43. Comparison of IRI-based pavement and bridge smoothness specifications (IRI in in/mi)

5. PREPARATION OF THE BRIDGE SMOOTHNESS SPECIFICATION

Although a complete survey among all states was not performed, it is known that only a few states have bridge smoothness specifications. Some of the states that have such specifications are Nebraska, Georgia, Oklahoma, and Kansas. The Nebraska specification is based on the PI measured with the California profilograph and does not have an incentive/disincentive program. The Georgia specification is based on PI using the 0.2-in (5.1-mm) blanking band measured with the Rainhart profilograph and it also does not have an incentive/disincentive program. On the other hand, Oklahoma and Kansas do have incentive/disincentive programs. Oklahoma's program is based on the 0.2-in (5.1-mm) blanking band PI measured with the California profilograph, whereas the Kansas specification is based on the null blanking band measured with the California profilograph. Table 2 shows a comparison between these four bridge smoothness specifications. The preliminary bridge smoothness specification for Illinois is shown in Appendix K.

Some states in the US, such as Pennsylvania and Texas, are developing specifications for measuring pavement profile using an inertial profiler. A draft of the Pennsylvania specification is shown in Appendix L, and a draft of the Texas specification is shown in Appendix M. Texas also has a specification for a lightweight profiler, as shown in Appendix N.

A standard is set in ASTM E 950-98 for measuring profile entitled "Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an

Accelerometer Established Inertial Profiling Reference." A copy of this ASTM standard is shown in Appendix O. There is also a NCHRP report prepared by Karamihas and Gillespie (1999) that provides guidelines for measuring longitudinal pavement profile.

Table 2. Comparison between different bridge smoothness specifications

Item	Nebraska	Georgia	Oklahoma	Kansas	Illinois (preliminary)
Smoothness index	PI (0.2-in BB)	PI (0.1-in BB)	PI (0.2-in BB)	PI (null BB)	IRI
Measuring equipment	California profilograph	Rainhart profilograph	California profilograph	California profilograph	Lightweight profiler
Lanes	All lanes	All lanes	All lanes	All lanes	All lanes
Number of passes required per lateral location	One	One	One	One	One pass is sufficient due to excellent repeatability.
Number of passes per lane	One	Two	One	Two	One
Lateral location within lanes	3.3 ft (1 m) from the outside lane line	Right and left wheel paths	Either wheel path	3.3 ft (1 m) from the lane edges	3 ft from the outer lane edge
Longitudinal testing locations	Bridge deck and approach slabs	Bridge deck and approach slabs	Bridge deck and approach slabs	Bridge deck excluding the first (or last) 15 ft when the Contractor is not responsible for adjacent pavement	Bridge deck and approach slabs
Range of smoothness index for 100 percent pay	PI (0.2 in BB) of 27 in/mi (0.426 mm/m)	PI (0.2 in BB) of 15 in/mi	PI (null BB) between 20.1 and 25 in/mi)	PI (null BB) between 30.1 and 50 in/mi)	Start with an IRI between 105 to 125 in/mi. This IRI could be achieved either before or after grinding to receive incentive/disincentives.

Table 2. Comparison between different bridge smoothness specifications (Continued)

Item	Nebraska	Georgia	Oklahoma	Kansas	Illinois (preliminary)
Incentives/disincentives	No	No	Yes	Yes	Yes, very important.
Pay incentives either before corrections or after corrections are made?	–	It does not specify	Yes	No, only before. Only in case of replacement, the payment adjustment is made after correction.	Yes, since all that matters is that bridge is smooth.
Identification of areas where grinding correction is required	If PI is greater than 27 in/mi or bumps exceeding 0.16 in from the 0.2-in BB	If PI is greater than 15 in/mi or bumps (or depression) exceeding 0.2 in from the BB	If PI is greater than 35 in/mi or bumps in excess of 0.4 in (without BB)	If PI is greater than 40 in/mi or bumps in excess of 0.4 in	Yes, when IRI > 150 in/mi, or deviations (bumps or dips) greater than 0.4 in
Corrective methods	Diamond grinding at a maximum depth of 0.5 in (13 mm) or replacement (entire width)	Special specification	No special requirements but it must be approved by the Engineer	According to the contractor but impact devices are not allowed (entire width)	Diamond grinding or replacement (entire width)
Equipment and criterion used at special surfaces	Straightedge (deviation not greater than 0.118 in)	Straightedge (deviation not greater than 0.125 in)	None	Straightedge (deviation not greater than 0.125 in)	Straightedge (deviation not greater than 0.15 in)
Test section length	100 ft (30.5 m)	Does not specify	0.05 mi	0.1 mi	0.05 mi

6. CONCLUSIONS

Several roughness indices were studied, including PI, IRI, and RN. After analyzing these indices, IRI was selected as the index and the K.J. Law Lightweight Profiler was the equipment chosen to measure the selected index. This decision was based on the advantages and disadvantages of each index and piece of equipment.

Since there is not much experience at this time about what IRI values should be specified for new bridges, a literature review of the existing bridge and pavement smoothness specifications across the US was conducted. Values of smoothness index based on parameters other than IRI, such as PI, were converted to IRI using some of the proposed correlations found in the literature. A new correlation between PI and IRI was also developed using the IDOT bridge smoothness data.

Twenty bridges in the state of Illinois were tested using a Lightweight Profiler. The repeatability of the profiles measured with this device is very good. Although K.J. Law was the manufacturer used in this study, the same performance would be expected for another lightweight device.

This study shows that bridges are much rougher than highway pavements. The majority of this roughness was located within the bridge system (bridge deck plus approach pavements). The full profiles for the bridges had an average IRI of 168 in/mi (2.65m/km), whereas typical initial IRI values for highway pavements range from 50 to 95 in/mi (0.79 to 1.50 m/km).

The joints pose a major problem, as can be seen with the occurrence of spikes at the joint locations, but the removal of the joints would not significantly improve the smoothness. Many of these spikes are not as large as some of the other bumps and dips in the profiles, so removing the spikes would not affect the smoothness values as much as initially suspected. Software is available (from the lightweight profiler manufacturers) to remove the joints from the analysis prior to IRI calculation. Another reason removing the joints will not greatly increase smoothness is the fact that many of these spikes gradually slope up to the joint and then slope down after the joint, with the joint width only being as wide as the peak. Removing the joints from the computation of IRI in these situations would still leave the very large bump in the profile.

Unlike the removal of the joints, the grinding analysis was shown to vastly improve the smoothness of the profiles. Assuming that the pavement could be ground to a maximum bump size of 0.2 in (5.1 mm), the average IRI could be reduced from 168 in/mi to 127 in/mi (2.65 and 2.00 m/km). This large increase in smoothness was observed in almost all of the profiles, validating Georgia DOT's grinding specifications as a major component in the reduction of bridge roughness.

There are not many bridge smoothness specifications in the US. Some of the states that have such specifications are Nebraska, Georgia, Oklahoma, and Kansas. All of these states' specifications are based on PI measured with the profilograph. A complete comparison between their specifications and the new IDOT bridge smoothness specification is presented. Based on the test results and the existing smoothness specification, a draft of the IDOT bridge smoothness specification is proposed.

7. REFERENCES

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Appendix A – List of All Bridges Initially Considered

List of Structures for Profiler Testing

Test site	Structure number	Facility carried	Feature crossed	Number of spans	Longest span	Length of structure	Type of beams	Skew	Profile
1*	069-0035	I 72 EB	ICG RR	3	54.0 ft (16.5 m)	151.3 ft (46.1 m)	Steel continuous	0°	Vertical Curve
2	069-0036	I 72 WB	ICG RR	3	54.0 ft (16.5 m)	151.3 ft (46.1 m)	Steel continuous	0°	Vertical Curve
3	069-0038	I 72 EB	S. Fk. Mauvaise Terre	2	82.0 ft (25.0 m)	168.0 ft (51.2	Steel continuous	28°	Slight Sag
4*	069-0039	I 72 WB	S. Fk. Mauvaise Terre	2	82.0 ft (25.0 m)	168.0 ft (51.2	Steel continuous	28°	Slight Sag
5*	069-0040	I 72 EB	IL 104 & B&N RR	2	111.0 ft (33.8 m)	268.3 ft (81.8 m)	Steel continuous	3°	Vertical Curve
6	069-0041	I 72 WB	IL 104 & B&N RR	2	111.0 ft (33.8 m)	268.3 ft (81.8 m)	Steel continuous	3°	Vertical Curve
7	069-0042	I 72 EB	Mauvaise Terre Creek	2	123.0 ft (37.5 m)	252.0 ft (76.8 m)	Steel continuous	0°	Slight Sag Curve
8*	069-0043	I 72 WB	Mauvaise Terre Creek	2	124.0 ft (37.8 m)	252.0 ft (76.8 m)	Steel continuous	0°	Slight Sag Curve
9*	069-0048	I 72 EB	N. Fk Mauvaise Terre	3	80.0 ft (24.4 m)	239.5 ft (73.0 m)	Steel continuous	0°	Superelevation - Uphill
10	069-0049	I 72 WB	N. Fk Mauvaise Terre	3	80.0 ft (24.4 m)	239.5 ft (73.0 m)	Steel continuous	0°	Superelevation - Downhill
11*	069-0052	IL 123	I 72	2	108.0 ft (32.9 m)	252.0 ft (76.8 m)	Steel continuous	0°	Vertical Curve
12*	069-0055	I 72 WB	FAP 310	3	106.0 ft (32.3 m)	286.8 ft (87.4 m)	Steel continuous	0°	No Grade
13	069-0056	I 72 EB	FAP 310	3	106.0 ft (32.3 m)	240.0 ft (73.2 m)	Steel continuous	0°	No Grade
14*	069-0057	I 72 WB	Massey Lane TR 128	3	48.0 ft (14.6 m)	118.0 ft (36.0 m)	Steel continuous	6°	Uphill Grade
15	069-0058	I 72 EB	Massey Lane TR 128	3	48.0 ft (14.6 m)	142.0 ft (43.3 m)	Steel continuous	6°	Uphill Grade
16*	069-0059	I 72 WB	Spring Creek	3	49.0 ft (14.9 m)	138.0 ft (42.1 m)	Steel continuous	0°	Sag Curve

*Selected bridges

List of Structures for Profiler Testing (Continued)

Test site	Structure number	Facility carried	Feature crossed	Number of spans	Longest span	Length of structure	Type of beams	Skew	Profile
17*	069-0060	I 72 EB	Spring Creek	3	49.0 ft (14.9 m)	138.0 ft (42.1 m)	Steel continuous	0°	Sag Curve
18*	069-0064	IL 123	N. Fk. Mauvaise Terre	1	77.0 ft (23.5 m)	79.7 ft (24.3 m)	Steel	25°	Downhill Grade
19*	069-0072	TR 96	US 67	2	127.1 ft (38.7 m)	237.2 ft (72.3 m)	PPC (Bulb “T”)	12°	Vertical Curve
20*	069-0077	TR 157	US 67	2	100.7 ft (30.7 m)	205.4 ft (62.6 m)	PPC (I-Beam)	0°	Slight Grade
21*	069-0078	Morton Ave. (Old US 36)	US 67	2	128.4 ft (39.1 m)	247.7 ft (75.5 m)	PPC	21°	Slight Grade
22	069-0082	Old IL 121	Br. Kickapoo Creek	3	44.9 ft (13.7 m)	136.0 ft (41.5 m)	PPC (I-Beam)	0°	No Grade
23	069-0083	Old IL 121	Br. Kickapoo Creek	3	44.9 ft (13.7 m)	136.0 ft (41.5 m)	PPC (I-Beam)	0°	Slight Grade
24	069-0103	Old IL 121	Br. Kickapoo Creek	3	44.9 ft (13.7 m)	136.0 ft (41.5 m)	PPC (I-Beam)	0°	Vertical Curve
25*	084-0037	11th Street/ Hazel Dell	I 55 & I 72	2	177.9 ft (54.2 m)	360.9 ft (110.0 m)	Steel continuous	5°	Vertical Curve
26*	084-0078	I 72/US 36 EB	I 55 SB	3	153.0 ft (46.6 m)	347.0 ft (105.8 m)	Steel continuous	62°	Vertical Curve
27*	084-0127	I 72/US 36 EB	N&W RR	3	84.0 ft (25.6 m)	224.0 ft (68.3 m)	Steel continuous	50°	Vertical Curve
28	084-0128	I 72/US 36 WB	N&W RR	3	84.0 ft (25.6 m)	224.0 ft (68.3 m)	Steel continuous	50°	Vertical Curve
29	084-0148	I 72/US 36 WB	IL 54 & FAS 1613	2	80.0 ft (24.4 m)	232.0 ft (70.7 m)	Steel continuous	47°	Vertical Curve
30*	084-0149	I 72/US 36 EB	IL 54 & FAS 1613	2	80.0 ft (24.4 m)	232.0 ft (70.7 m)	Steel continuous	47°	Vertical Curve
31*	084-0205	IL 54	Sangamon River	5	185.0 ft (56.4 m)	852.6 ft (259.9 m)	Steel continuous	0°	Vertical Curve
32*	084-0207	IL 29	Sangamon River	4	270.0 ft (82.3 m)	875.7 ft (266.9 m)	Steel Girder	0°	Vertical Curve
33	084-0208	E. Lake Shore Drive	IC, C&IM RR	3	54.9 ft (16.7 m)	148.6 ft (45.3 m)	Steel continuous	0°	Vertical Curve

*Selected bridges

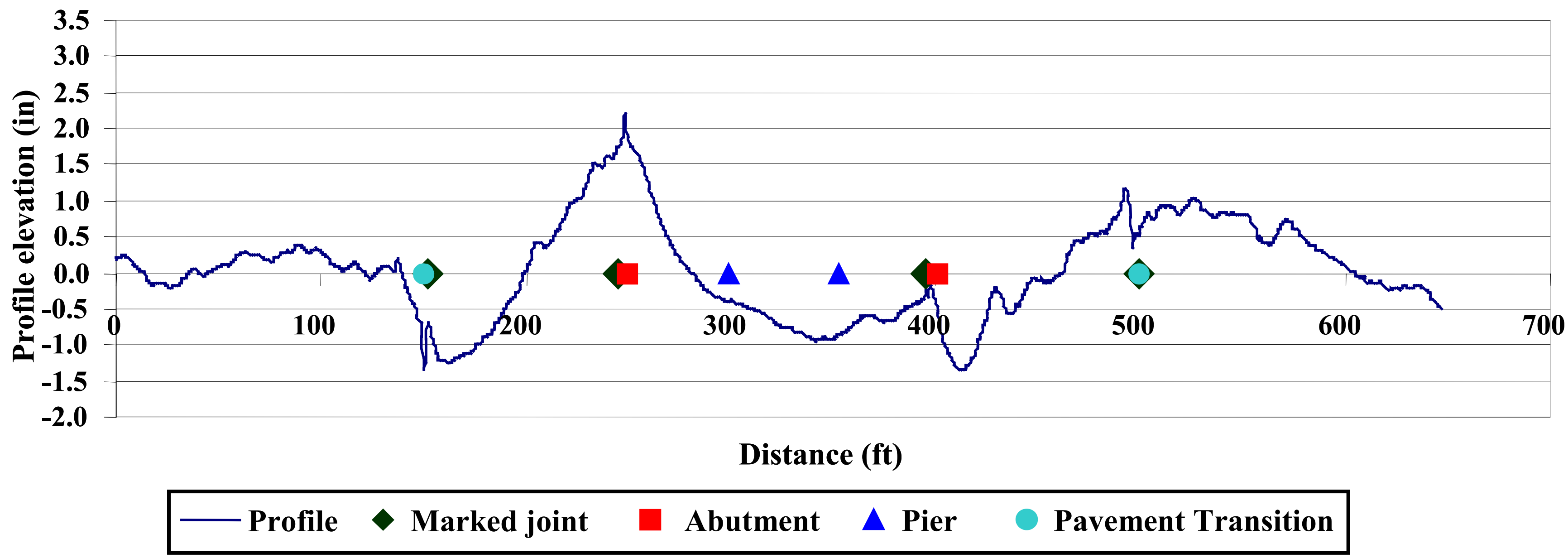
Appendix B – Total Length of Selected Test Sections

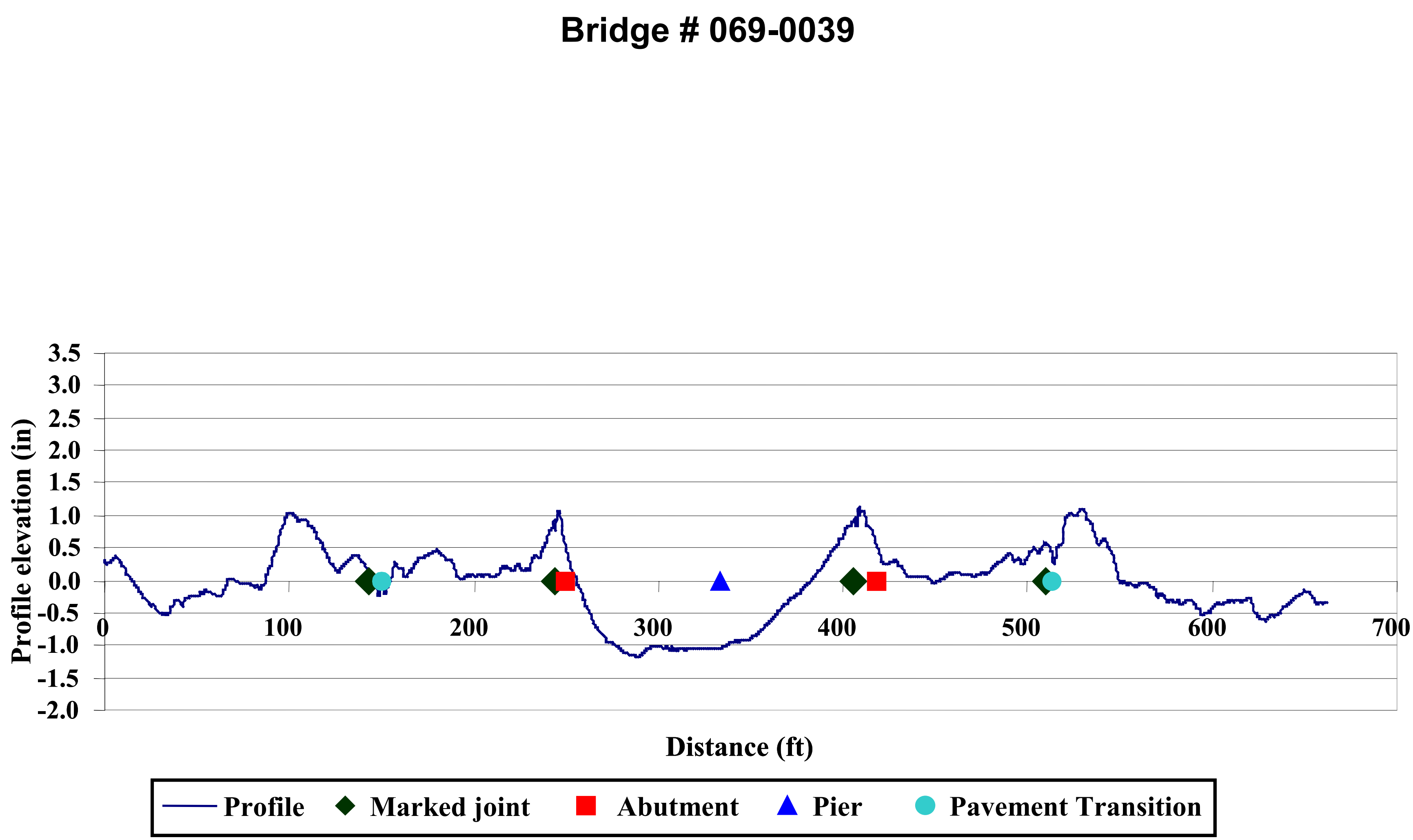
Total Length of Selected Test Sections

Bridge	Length (ft)	Total tested section (ft)	Front existing pavement (ft)	Bridge deck plus approach pavements (ft)	Rear existing pavement (ft)
069-0035	151.3	647.0	0.0 - 150.0	150.0 - 500.0	500.0 - 647.0
069-0039	168.0	662.5	0.0 - 150.0	150.0 - 513.0	513.0 - 662.5
069-0040	268.3	764.0	0.0 - 150.0	150.0 - 620.0	620.0 - 764.0
069-0043	252.0	748.5	0.0 - 150.0	150.0 - 600.0	600.0 - 748.5
069-0048	239.5	736.0	0.0 - 150.0	150.0 - 588.0	588.0 - 736.0
069-0052	252.0	654.5	0.0 - 200.0	200.0 - 452.0	452.0 - 654.5
069-0055	286.8	784.5	0.0 - 150.0	150.0 - 635.0	635.0 - 784.5
069-0057	118.0	616.0	0.0 - 150.0	150.0 - 468.0	468.0 - 616.0
069-0059	138.0	523.5	0.0 - 150.0	150.0 - 373.0	373.0 - 523.5
069-0060	138.0	521.0	0.0 - 150.0	150.0 - 370.0	370.0 - 521.0
069-0064	79.7	440.5	0.0 - 150.0	150.0 - 290.0	290.0 - 440.5
069-0072	237.2	595.0	0.0 - 150.0	150.0 - 444.0	444.0 - 595.0
069-0077	205.4	562.5	0.0 - 150.0	150.0 - 415.0	415.0 - 562.5
069-0078	247.7	704.5	0.0 - 150.0	150.0 - 554.0	554.0 - 704.5
084-0037	360.9	729.5	0.0 - 200.0	200.0 - 590.0	590.0 - 729.5
084-0078	347.0	626.5	0.0 - 150.0	150.0 - 497.0	497.0 - 626.5
084-0127	224.0	769.5	0.0 - 150.0	150.0 - 620.0	620.0 - 769.5
084-0149	232.0	740.0	0.0 - 200.0	200.0 - 540.0	540.0 - 740.0
084-0205	852.6	1310.0	0.0 - 200.0	200.0 - 1110.0	1110.0 - 1310.0
084-0207	875.7	1241.0	0.0 - 150.0	150.0 - 1090.0	1090.0 - 1241.0

Appendix C – Pier and Abutment Location

Bridge # 069-0035

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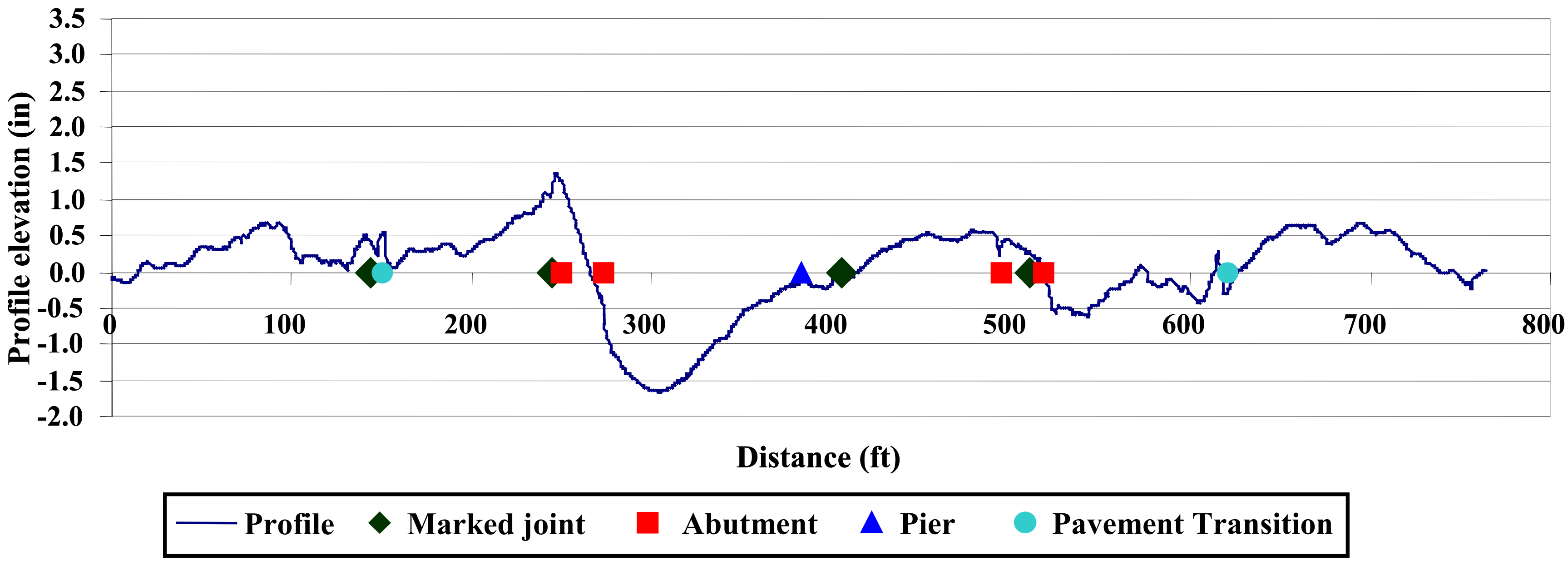
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
100
200
300
400
500
600
700
Distance (ft)
Profile
Marked joint
Abutment
Pier
Pavement Transition

Bridge # 069-0040



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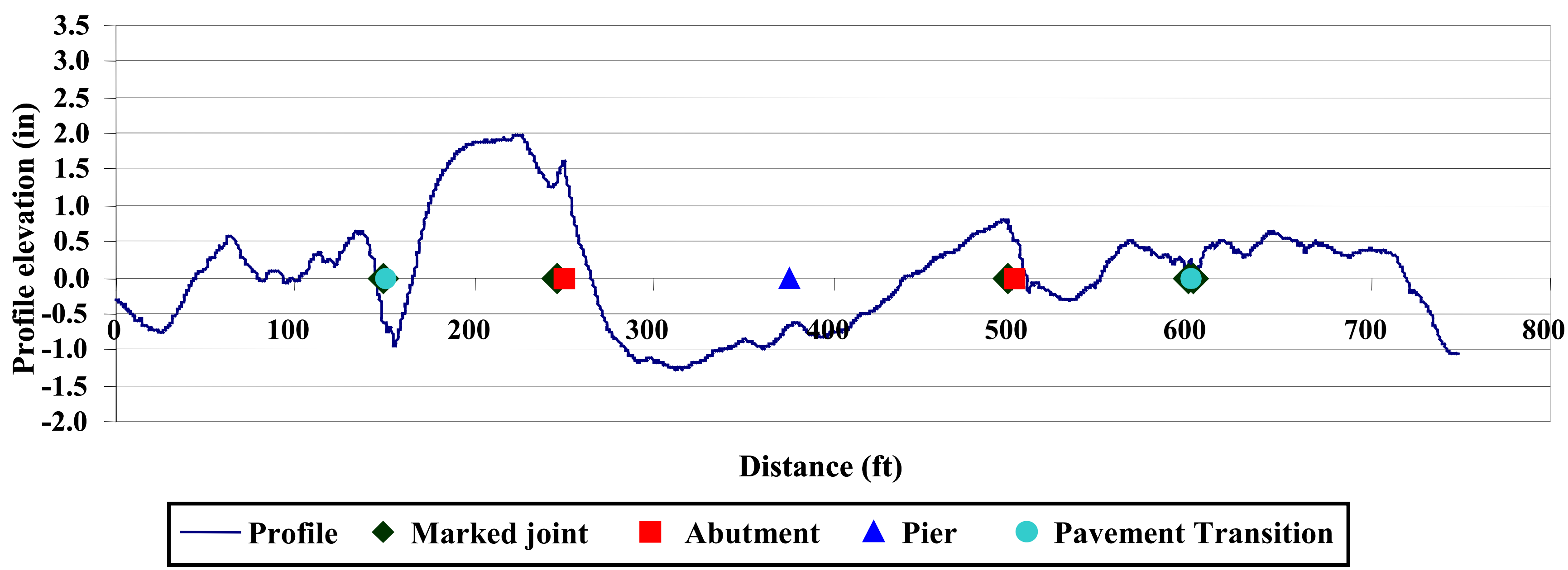

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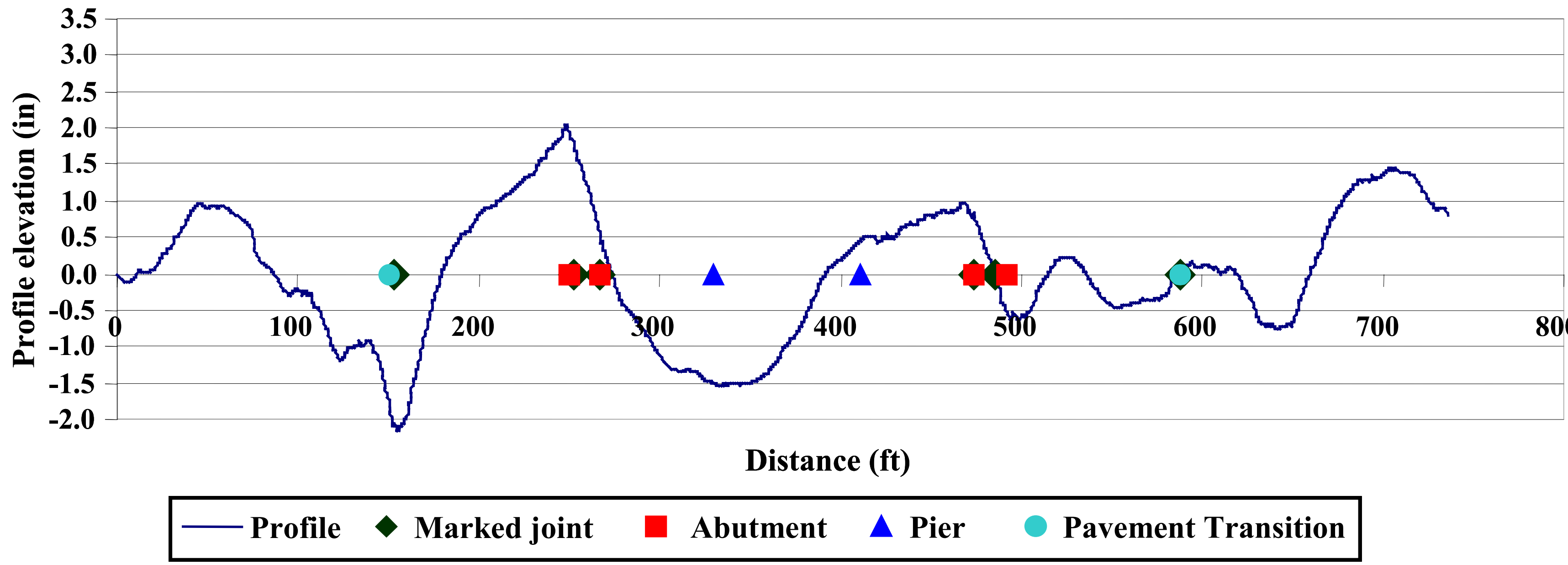

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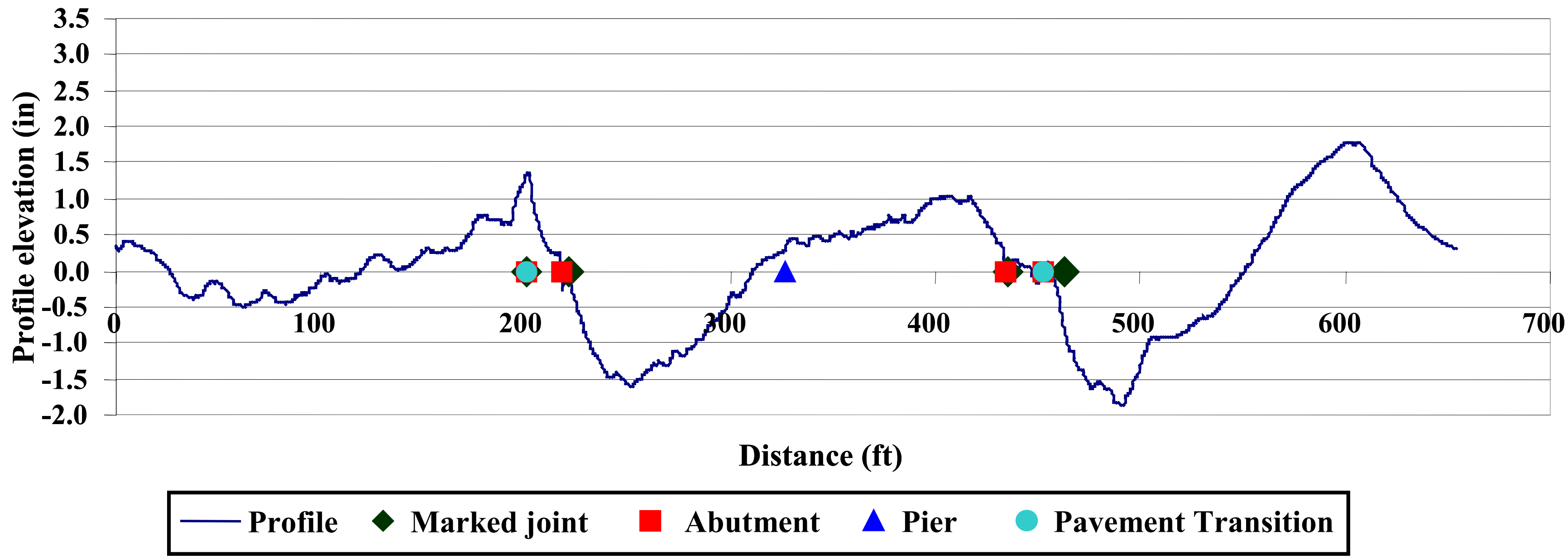
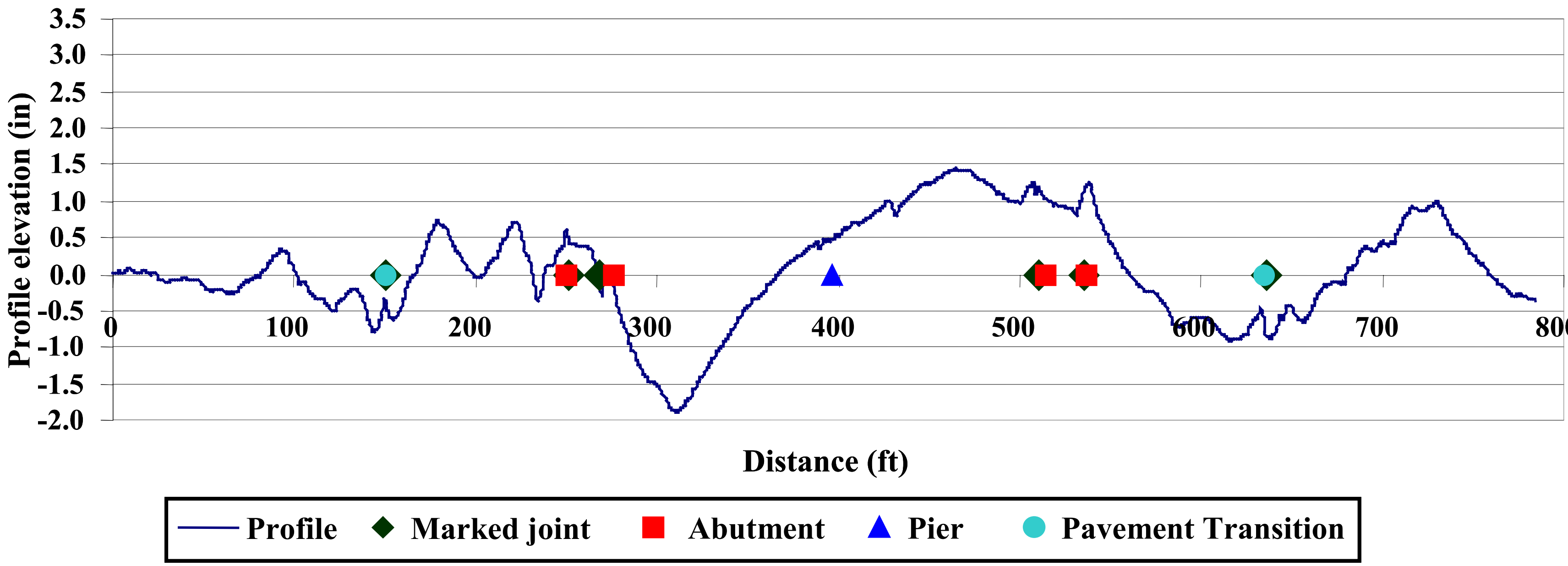
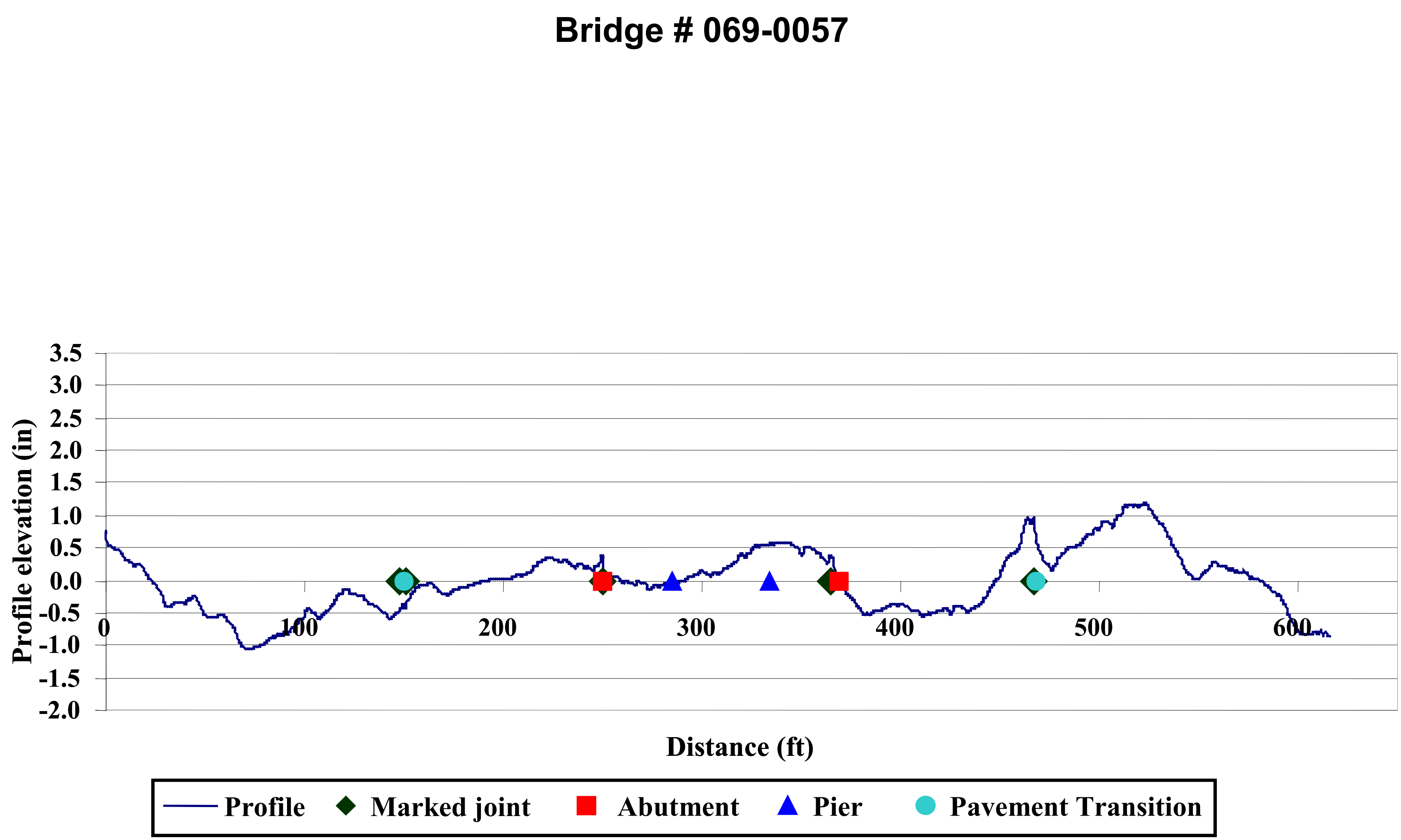


Bridge # 069-0055





Bridge # 069-0057
Profile elevation (in)
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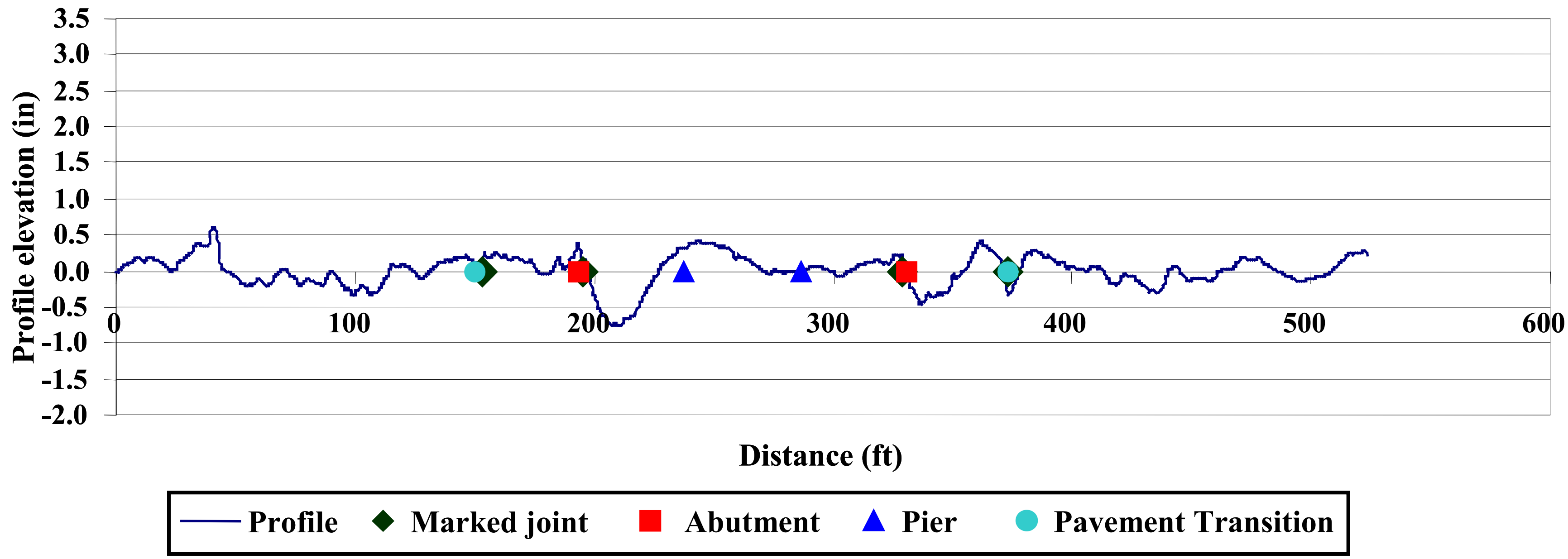
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
100
200
300
400
500
600
Distance (ft)
Profile
Marked joint
Abutment
Pier
Pavement Transition

Bridge # 069-0059



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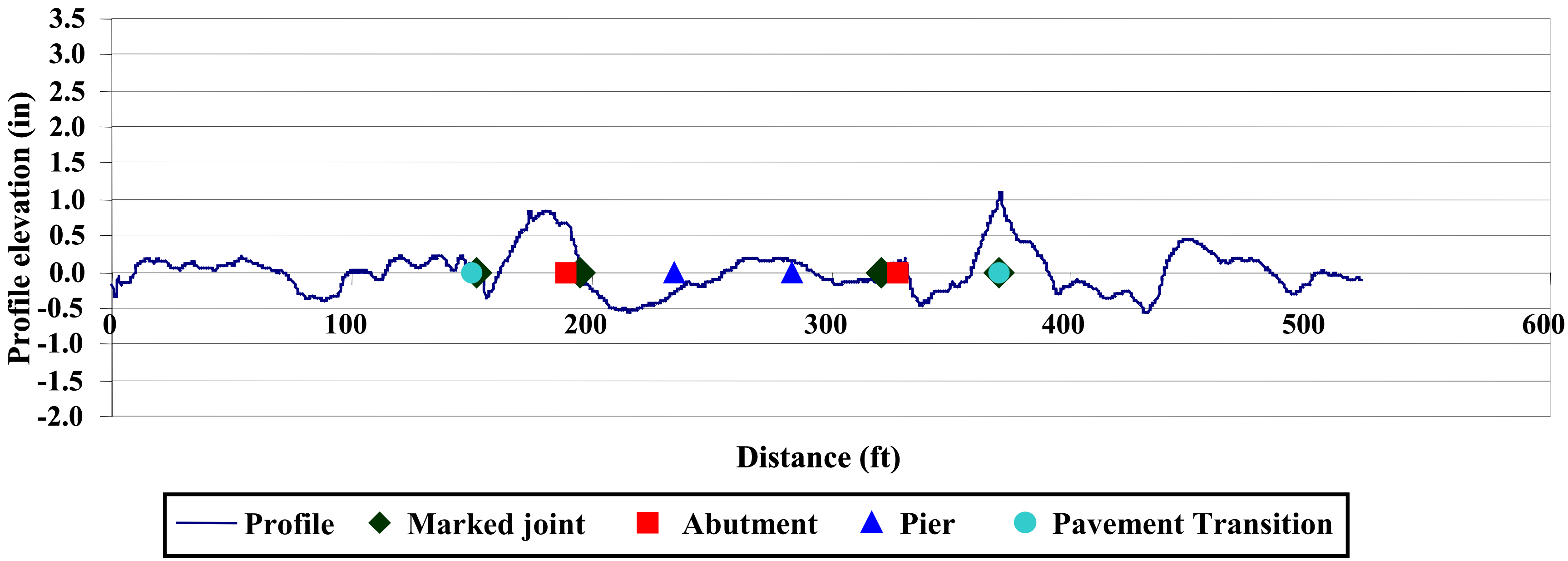

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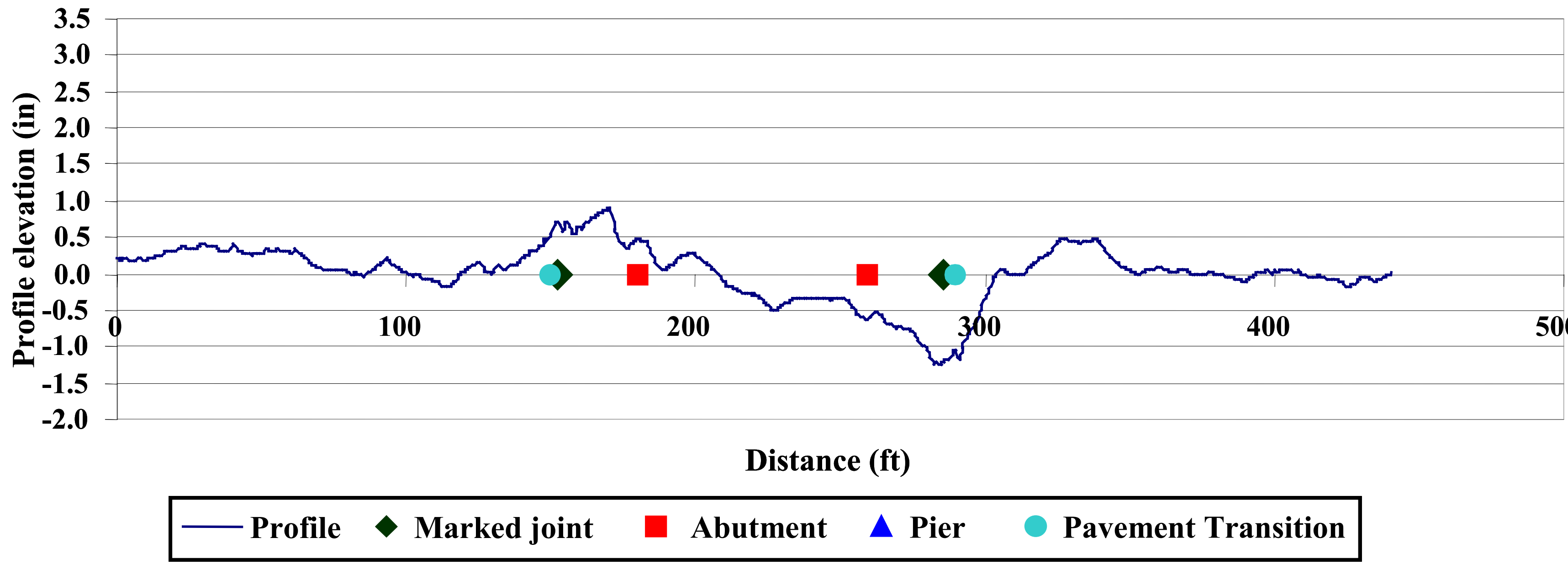

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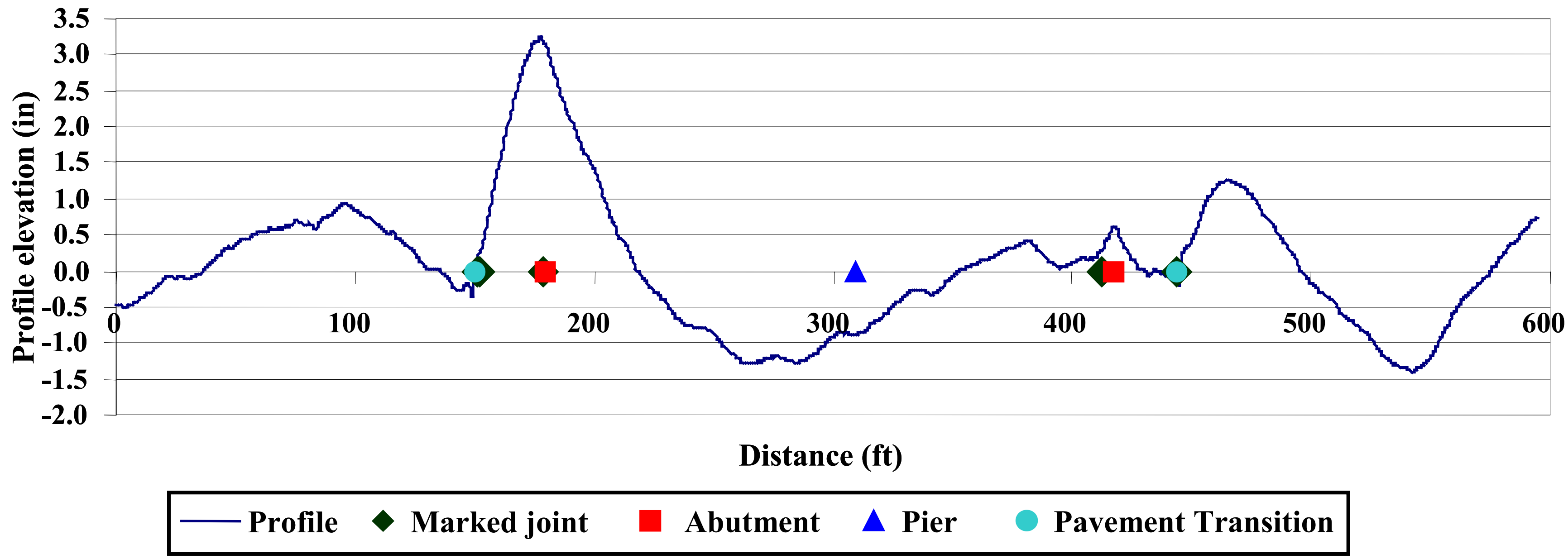

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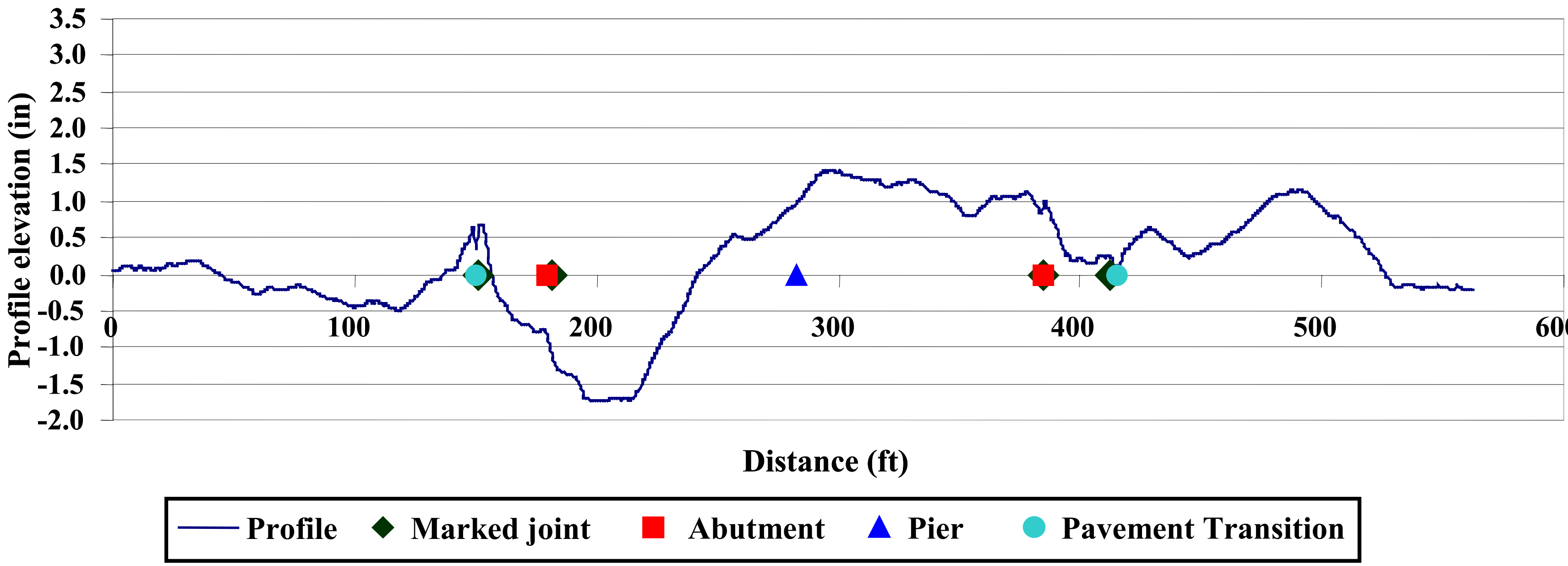

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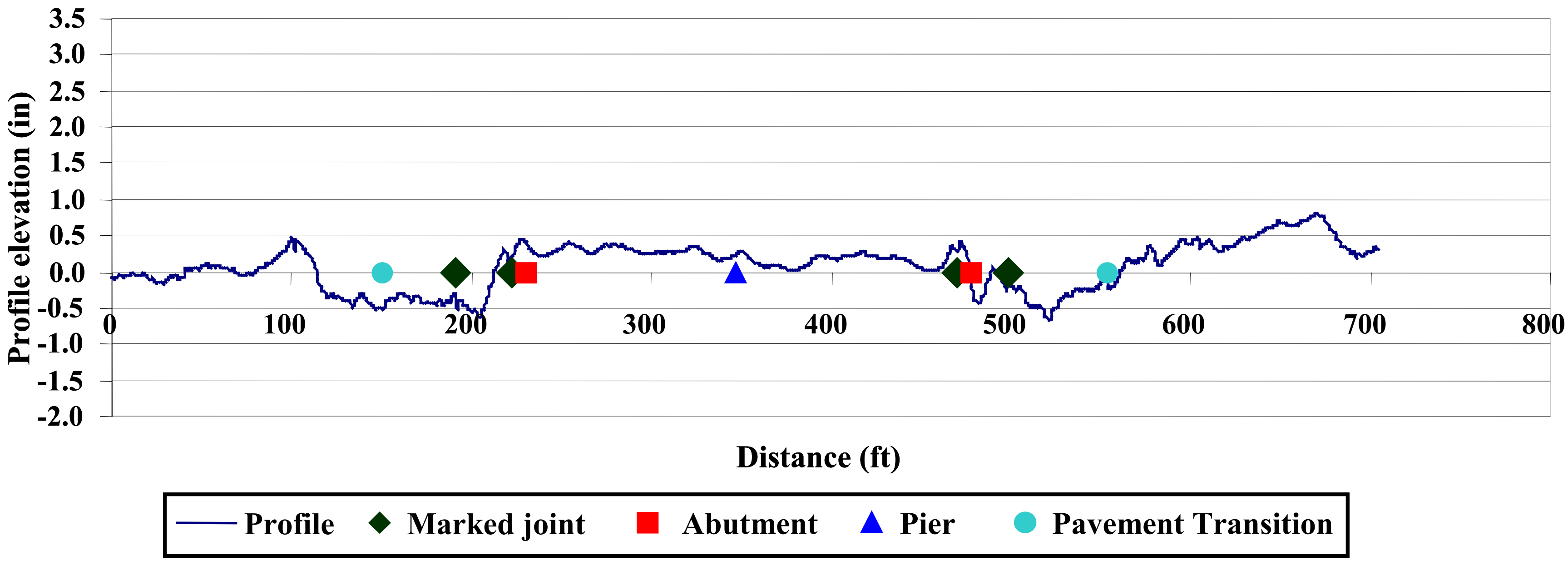

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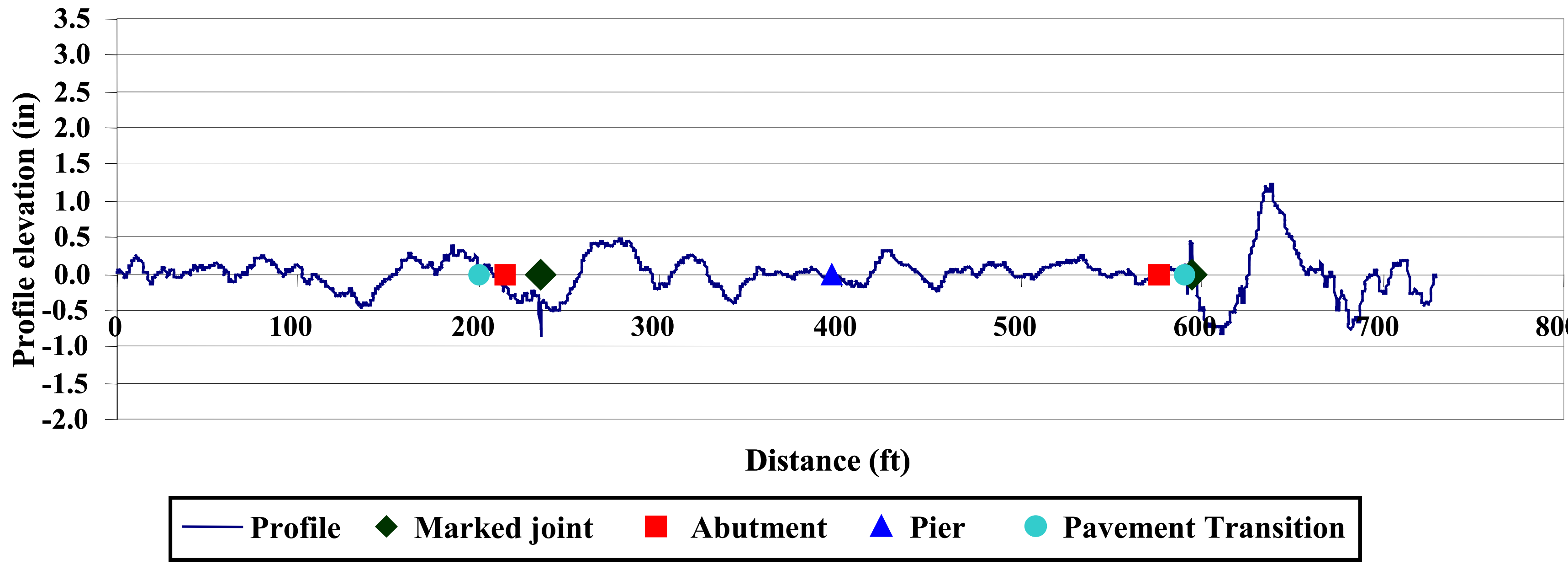

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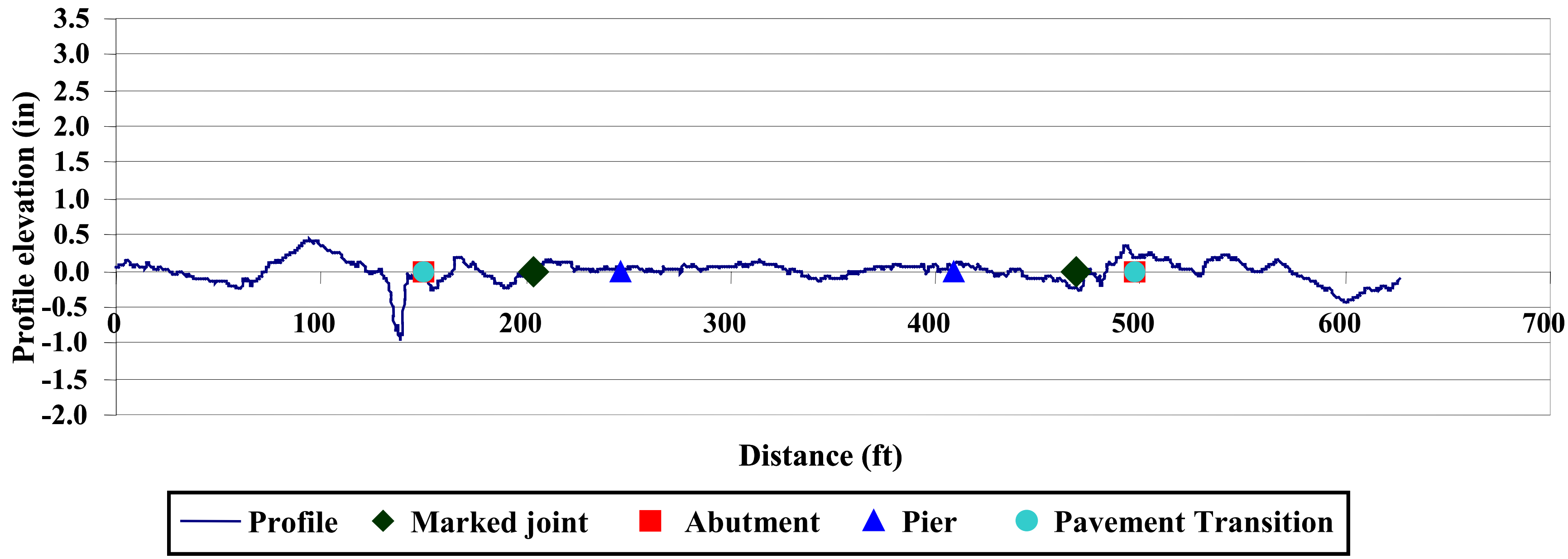

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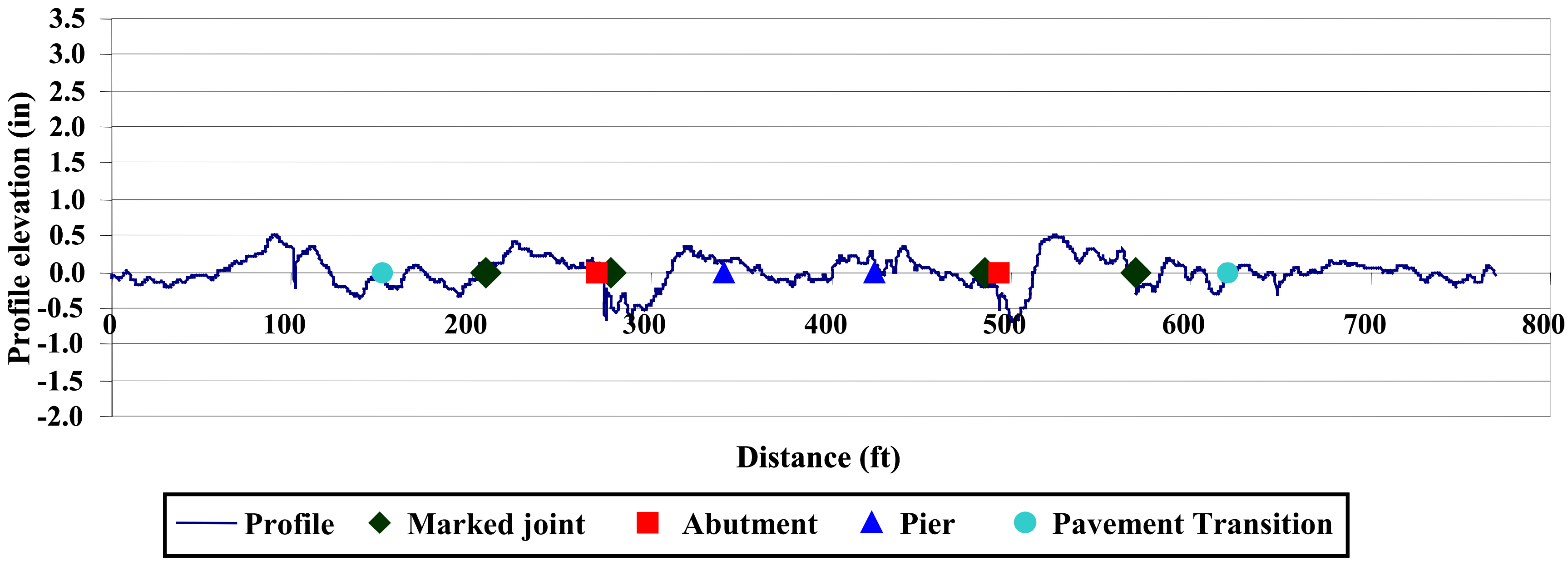

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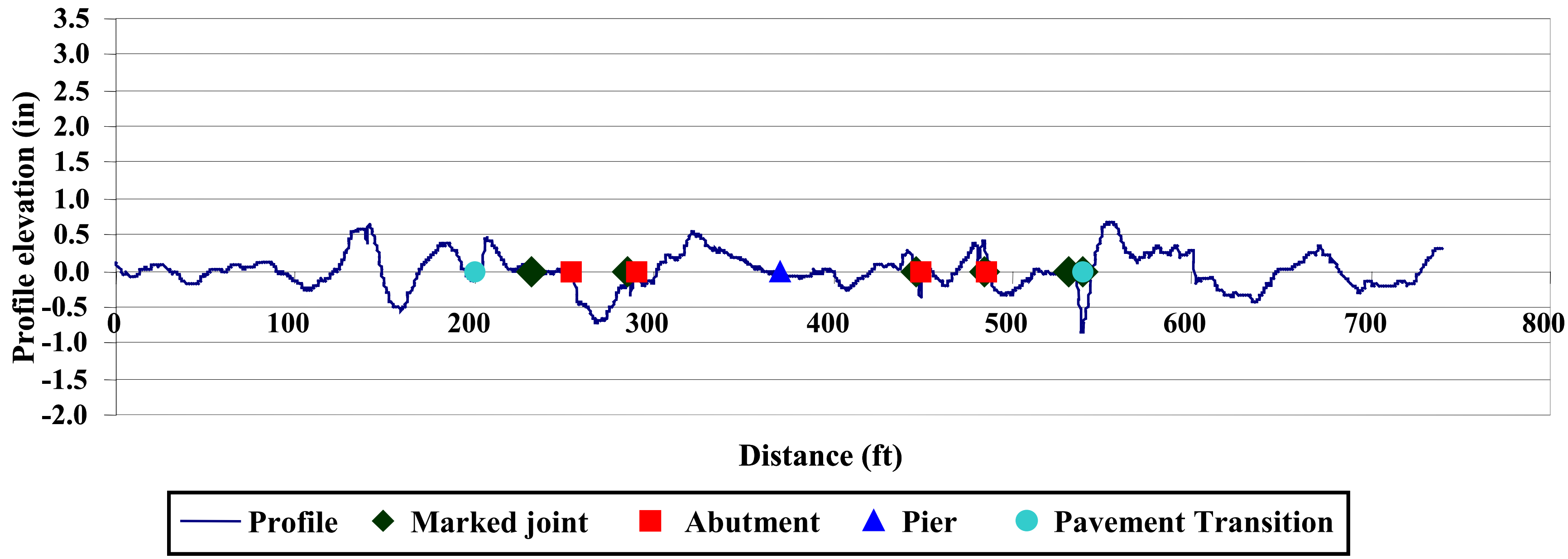

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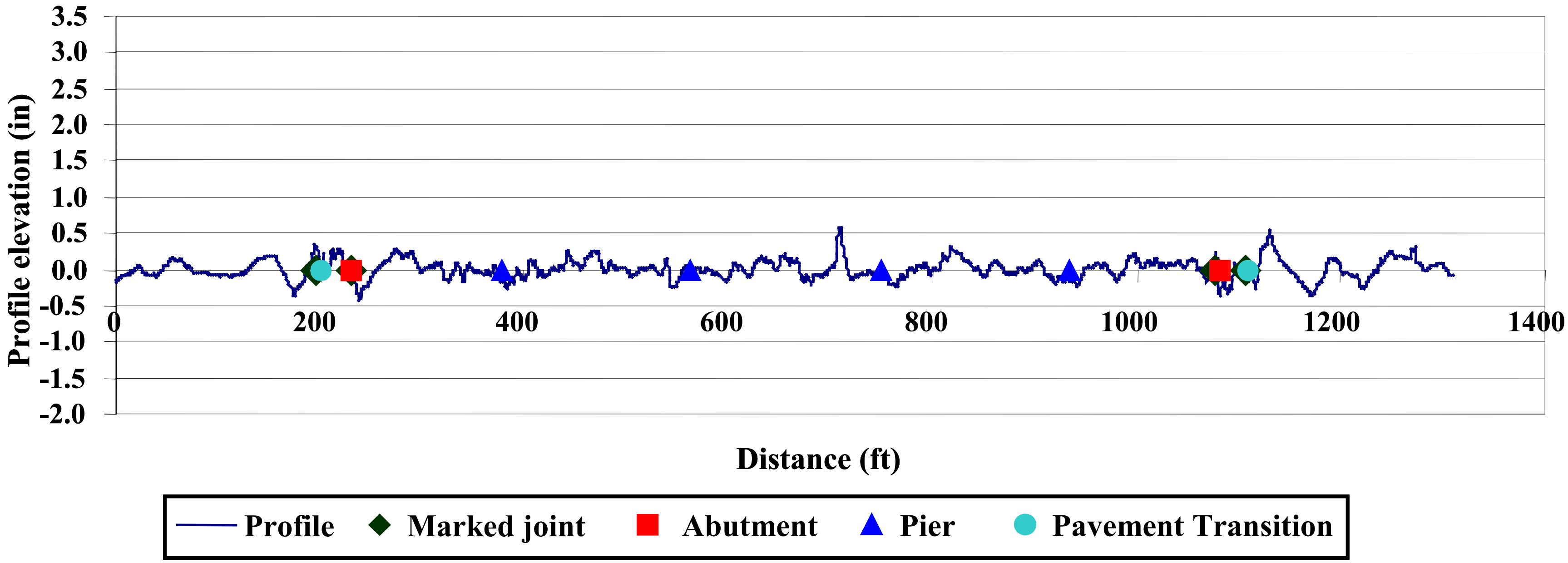

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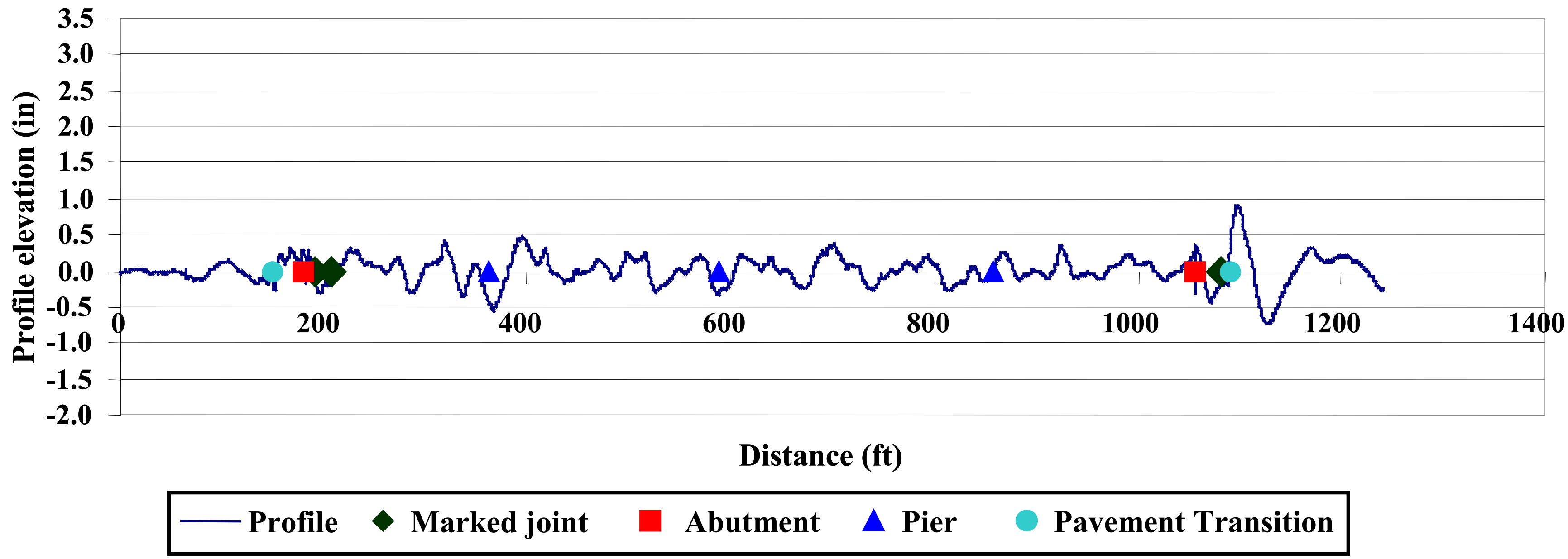


Appendix D – IRI and PI for All Bridges Tested

IRI and PI for All Bridges Tested

Monday 6/7/99

Bridge #	Facility Carried	Length	Pass#	IRI in/mi	PI (in/mi)
084-0207	IL 29	875.7 ft	1 2	156 171	40.5 46.7
084-0149	I 72/US 36 EB	232.0 ft	1* 2* 3	199 203 210	62.1 61.1 68.1
084-0127	I 72/US 36 EB	224.0 ft	1 2	194 198	42.0 52.1
084-0037	11th Street/Hazel Dell	360.9 ft	1 2	224 237	61.0 69.5
084-0078	I 72/US 36 EB	347.0 ft	1 2	131 147	23.5 34.3
084-0205	IL 54	852.6 ft	1 2	155 138	29.9 26.6

Tuesday 6/8/99

Bridge #	Facility Carried	Length	Pass#	IRI in/mi	PI (in/mi)
069-0060	I 72 EB	138.0 ft	1 2	192 203	56.0 49.1
069-0059	I 72 WB	138.0 ft	1 2	196 165	54.5 46.2
069-0052	IL 123	252.0 ft	1* 2* 3	162 165 178	47.2 42.1 44.4
069-0064	IL 123	79.7 ft	1 2	143 134	- -
069-0043	I 72 WB	252.0 ft	1* 2* 3* 4* 5	159 162 159 163 163	46.5 46.1 46.4 45.3 41.2
069-0039	I 72 WB	168.0 ft	1 2	183 169	50.5 39.8
069-0057	I 72 WB	118.0 ft	1 2	158 170	41.7 46.6
069-0035	I 72 EB	151.3 ft	1 2	193 159	54.3 41.1
069-0040	I 72 EB	268.3 ft	1 2	135 135	29.6 26.1
069-0048	I 72 EB	239.5 ft	1 2	165 159	41.1 39.4

* Repeated Right Wheel Path
+ Repeated Left Wheel Path

IRI and PI for All Bridges Tested (Continued)

Wednesday 6/9/99

Bridge #	Facility Carried	Length	Pass#	IRI in/mi	PI (in/mi)
069-0055	I 72 WB	286.8 ft	1	166	47.2
			2	164	47.7
069-0078	Morton Avenue (Old US 36)	247.7 ft	1	138	30.5
			2	123	22.7
069-0072	TR 96	237.2 ft	1	169	44.8
			2	143	32.4
069-0077	TR 157	205.4 ft	1*	145	39.4
			2*	144	36.2
			3*	147	36.6
			4*	145	36.0
			5+	147	35.9
			6+	145	35.3
			7+	145	38.6
			8+	149	38.5
069-0073	New Bridge	-	1	160	41.5
			2	97	17.8

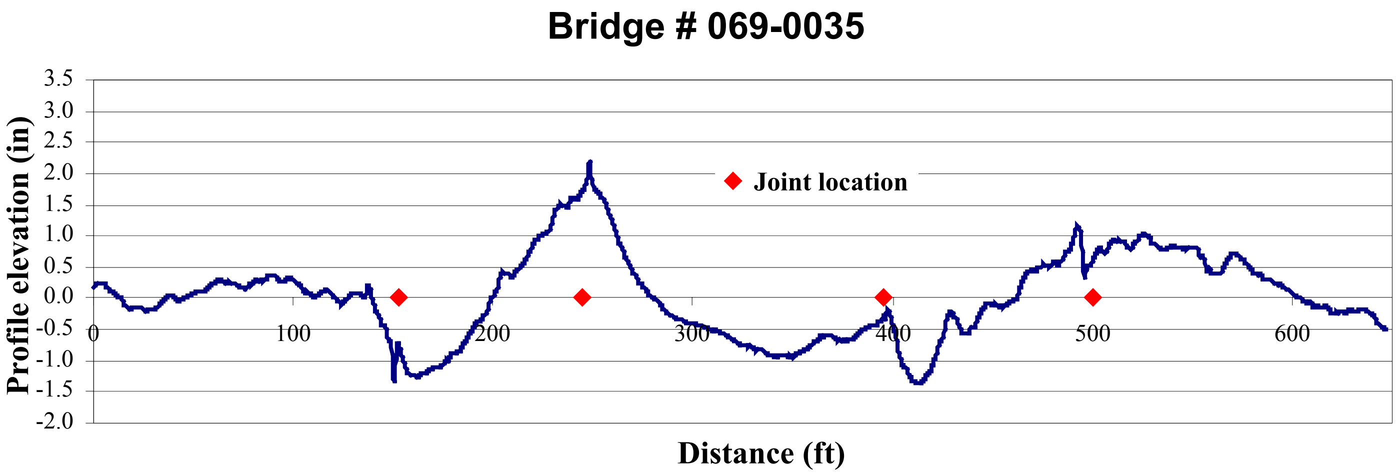
* Repeated Right Wheel Path
+ Repeated Left Wheel Path

Appendix E – IRI for the Right Wheel Path Considering the Total Section, the Bridge System, the Front and the Rear Approach Pavements

IRI for the Right Wheel Path Considering the Total Section, the Bridge System, the Front and the Rear Approach Pavements

Bridge	IRI (in/mi)			
	Total test section	Front approach	Bridge system	Rear approach
069-0035	193	146	225	138
069-0039	183	202	165	207
069-0040	135	131	144	89
069-0043	159	171	143	128
069-0048	165	160	166	141
069-0052	162	139	169	152
069-0055	166	142	175	144
069-0057	158	154	138	176
069-0059	196	208	215	149
069-0060	192	166	198	180
069-0064	143	106	175	129
069-0072	169	99	171	165
069-0077	145	89	179	117
069-0078	138	128	138	139
084-0037	224	162	158	490
084-0078	131	181	114	96
084-0127	194	163	222	128
084-0149	199	141	203	192
084-0205	155	86	169	159
084-0207	156	69	158	187
Min	**131**	**69**	**114**	**89**
Max	**224**	**208**	**225**	**490**
Average	**168**	**142**	**171**	**165**
Standard deviation	**25**	**38**	**30**	**82**

Appendix F – Bridge Summaries



Facility Carried: I 72 EB

Feature Crossed: ICG RR

Number of Spans: 3

Longest Span: 54.0 ft (16.5 m)

Total Length : 151.3 ft (46.1 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
193	2.30
159	2.78

Front Existing Pavement

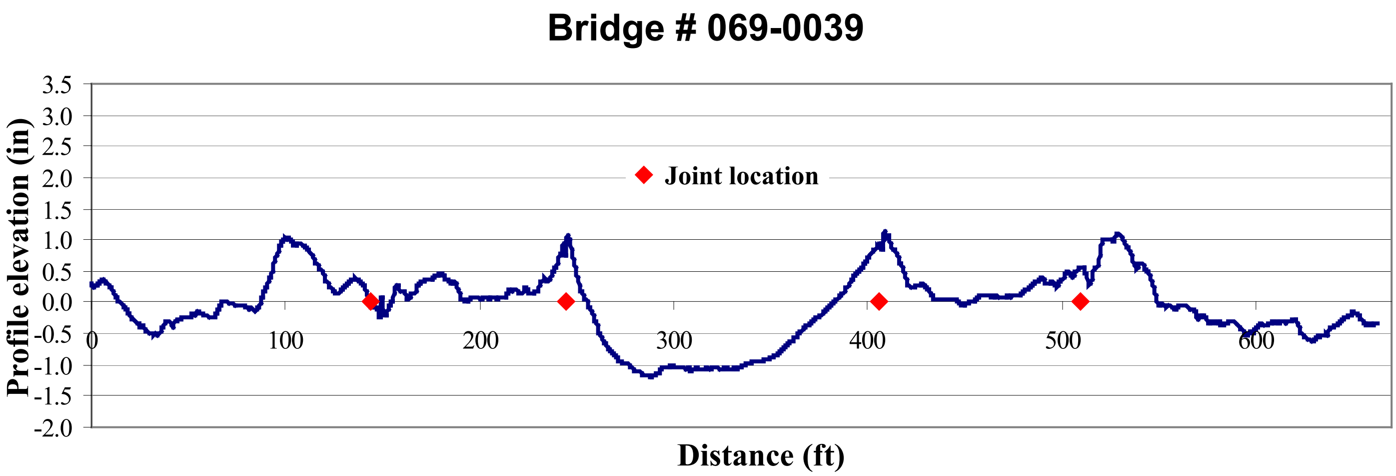
IRI (in/mi)	RN
146	2.77

Bridge Structure Smoothness

IRI (in/mi)	RN
225	2.04

Rear Existing Pavement

IRI (in/mi)	RN
138	3.08



Facility Carried: I 72 WB

Feature Crossed:
S. Fk. Mauvaise Terre

Number of Spans: 2

Longest Span: 82.0 ft (25.0 m)

Total Length: 168.0 ft (51.2 m)

Type of Beams: Steel Continuous

Skew: 28°

Profile: Slight Sag

Total Test Section Smoothness

IRI (in/mi)	RN
183	2.61
169	2.80

Front Existing Pavement

IRI (in/mi)	RN
202	2.67

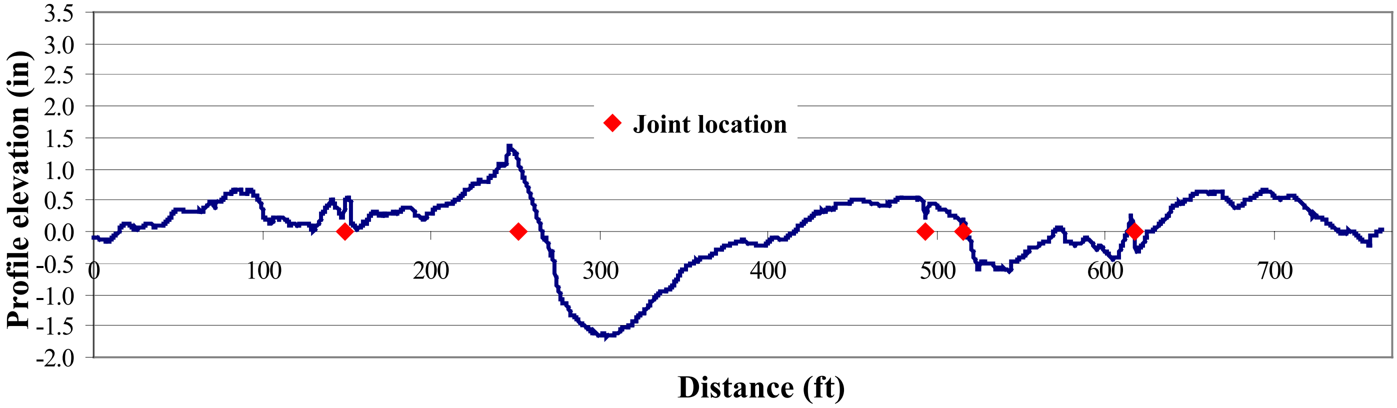
Bridge Structure Smoothness

IRI (in/mi)	RN
165	2.60

Rear Existing Pavement

IRI (in/mi)	RN
207	2.61

Bridge # 069-0040



Facility Carried: I 72 EB

Feature Crossed:
IL 104 & B&N RR

Number of Spans: 2

Longest Span: 111.0 ft (33.8 m)

Total Length: 268.3 ft (81.8 m)

Type of Beams: Steel Continuous

Skew: 3°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
135	2.88
135	2.85

Front Existing Pavement

IRI (in/mi)	RN
131	2.91

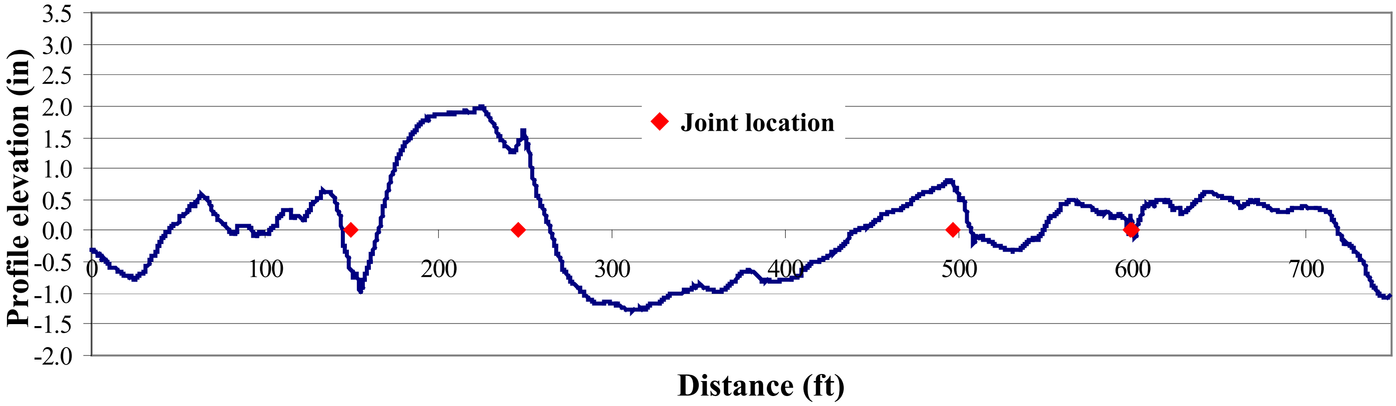
Bridge Structure Smoothness

IRI (in/mi)	RN
144	2.79

Rear Existing Pavement

IRI (in/mi)	RN
89	3.44

Bridge # 069-0043



Facility Carried: I 72 WB

Feature Crossed:
Mauvaise Terre Creek

Number of Spans: 2

Longest Span: 124.0 ft (37.8 m)

Total Length: 252.0 ft (76.8 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Slight Sag Curve

Total Test Section Smoothness

IRI (in/mi)	RN
159	3.08
163	2.91

Front Existing Pavement

IRI (in/mi)	RN
171	2.90

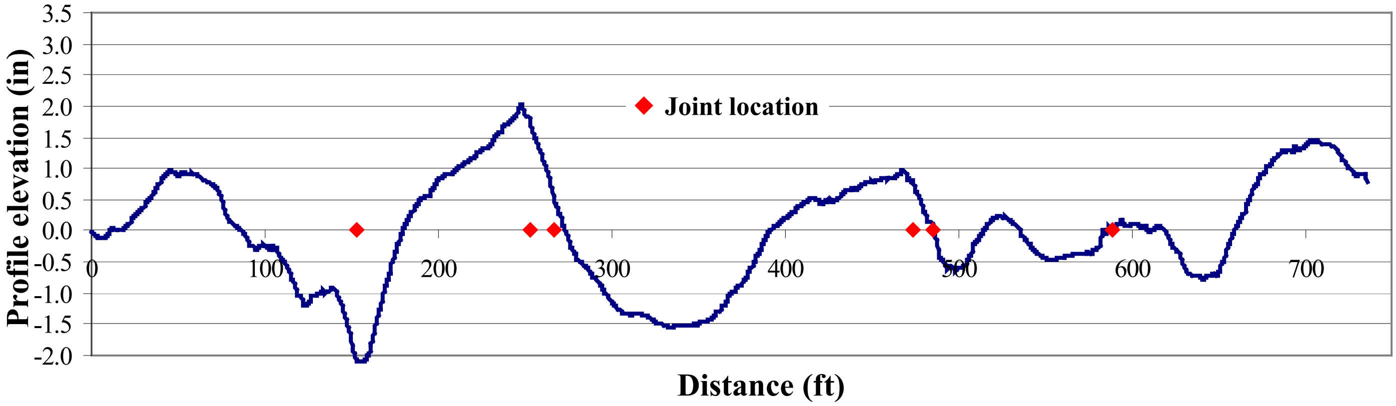
Bridge Structure Smoothness

IRI (in/mi)	RN
143	2.86

Rear Existing Pavement

IRI (in/mi)	RN
128	3.08

Bridge # 069-0048



Facility Carried: I 72 EB

Feature Crossed:
N. Fk Mauvaise Terre

Number of Spans: 3

Longest Span: 80.0 ft (24.4 m)

Total Length: 239.5 ft (73.0 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Superelevation - Uphill

Total Test Section Smoothness

IRI (in/mi)	RN
165	3.34
159	2.98

Front Existing Pavement

IRI (in/mi)	RN
160	3.33

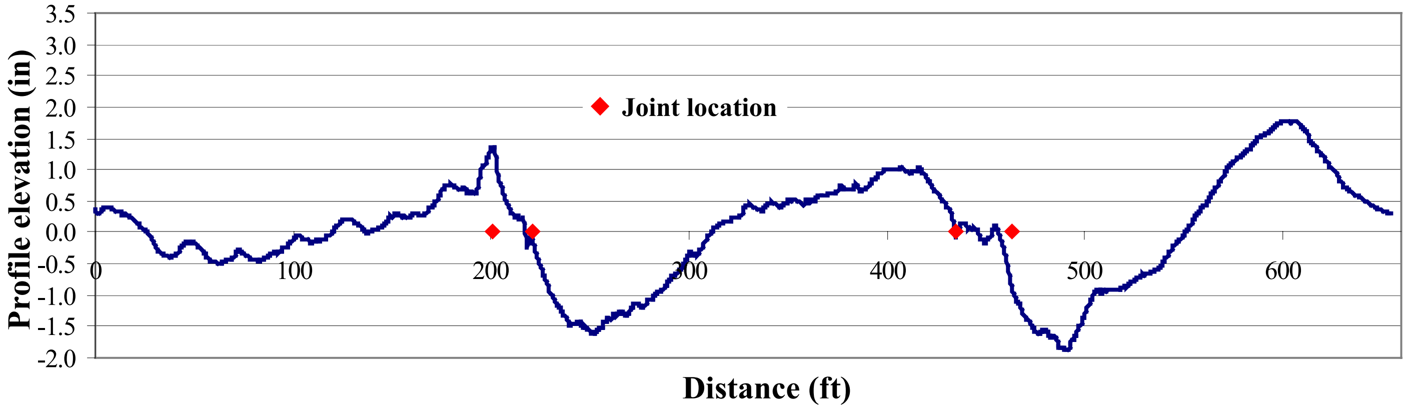
Bridge Structure Smoothness

IRI (in/mi)	RN
166	3.25

Rear Existing Pavement

IRI (in/mi)	RN
141	3.43

Bridge # 069-0052



Facility Carried: IL 123

Feature Crossed: I 72

Number of Spans: 2

Longest Span: 108.0 ft (32.9 m)

TotalLength: 252.0 ft (76.8 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
162	2.76
178	2.56

Front Existing Pavement

IRI (in/mi)	RN
139	3.18

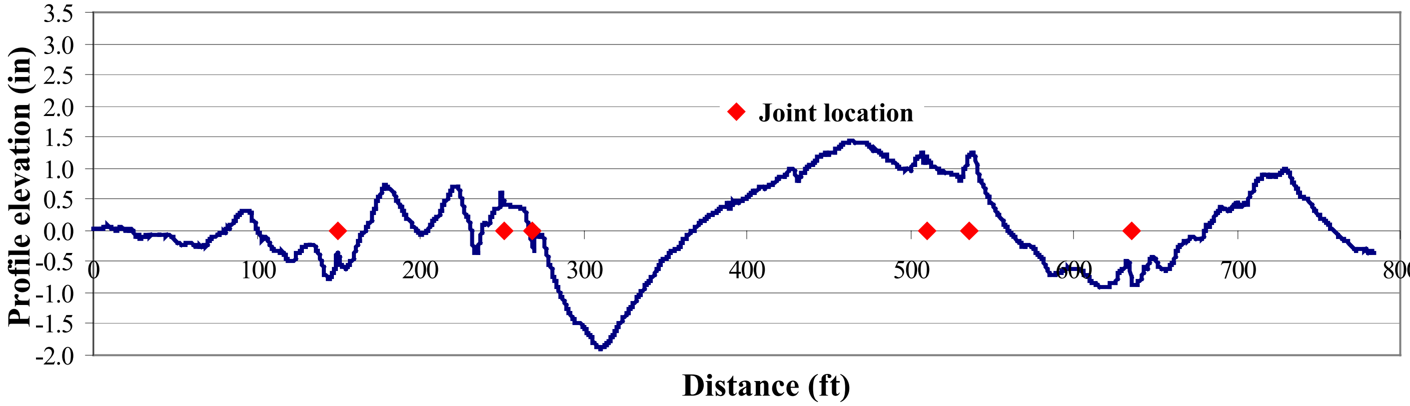
Bridge Structure Smoothness

IRI (in/mi)	RN
169	2.49

Rear Existing Pavement

IRI (in/mi)	RN
152	3.15

Bridge # 069-0055



Facility Carried: I 72 WB

Feature Crossed: FAP 310

Number of Spans: 3

Longest Span: 106.0 ft (32.3 m)

Length: 286.8 ft (87.4 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: No Grade

Total Test Section Smoothness

IRI (in/mi)	RN
166	2.79
164	2.79

Front Existing Pavement

IRI (in/mi)	RN
142	3.13

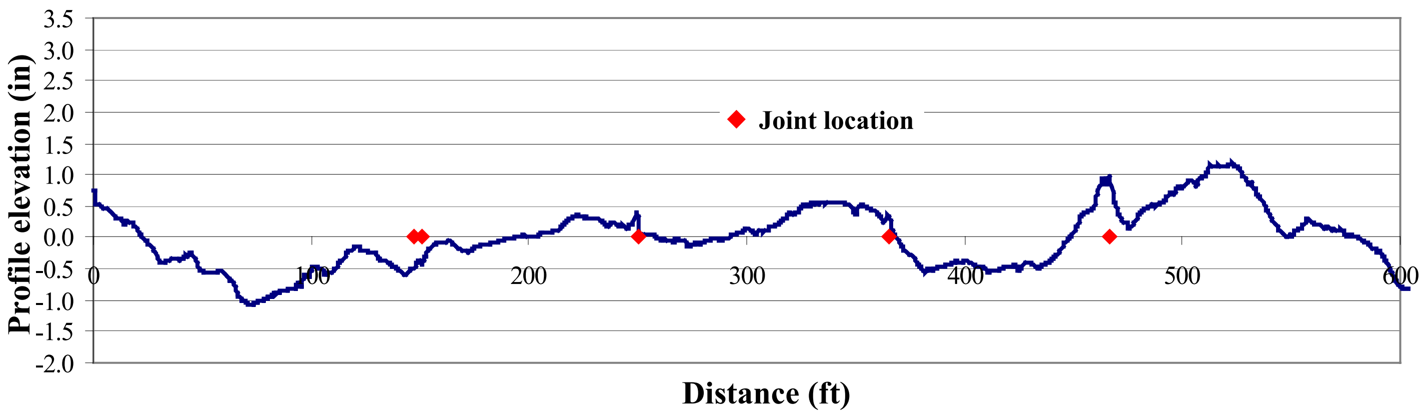
Bridge Structure Smoothness

IRI (in/mi)	RN
175	2.73

Rear Existing Pavement

IRI (in/mi)	RN
144	2.92

Bridge # 069-0057



Facility Carried: I 72 WB

Feature Crossed:
Massey Lane TR 128

Number of Spans: 3

Longest Span: 48.0 ft (14.6 m)

Length: 118.0 ft (36.0 m)

Type of Beams: Steel Continuous

Skew: 6°

Profile: Uphill Grade

Total Test Section Smoothness

IRI (in/mi)	RN
158	2.89
170	2.74

Front Existing Pavement

IRI (in/mi)	RN
154	2.85

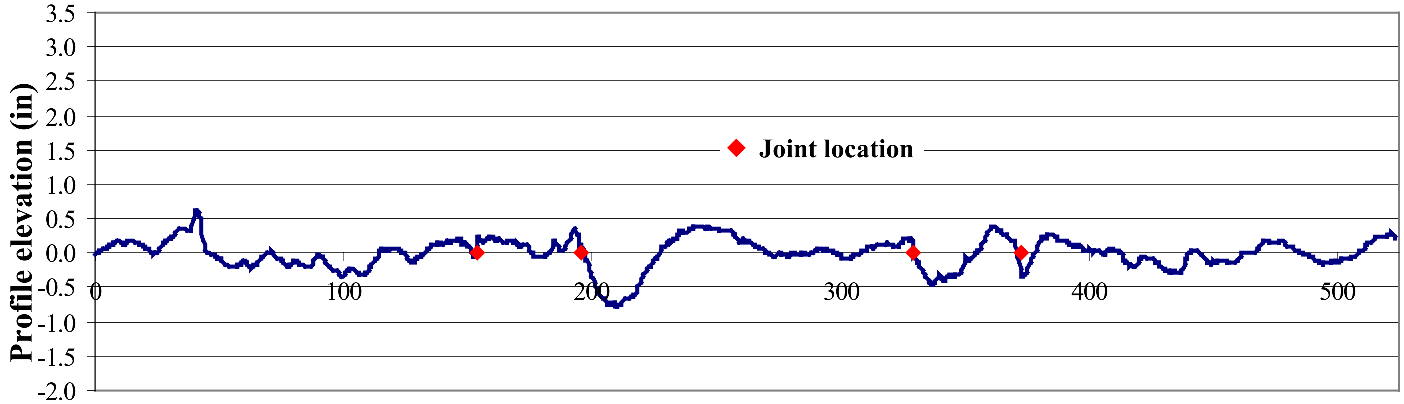
Bridge Structure Smoothness

IRI (in/mi)	RN
138	2.97

Rear Existing Pavement

IRI (in/mi)	RN
176	2.88

Bridge # 069-0059



Facility Carried: I 72 WB

Feature Crossed: Spring Creek

Number of Spans: 3

Longest Span: 49.0 ft (14.9 m)

Total Length: 138.0 ft (42.1 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Sag Curve

Total Test Section Smoothness

IRI (in/mi)	RN
196	2.62
165	2.84

Front Existing Pavement

IRI (in/mi)	RN
208	2.60

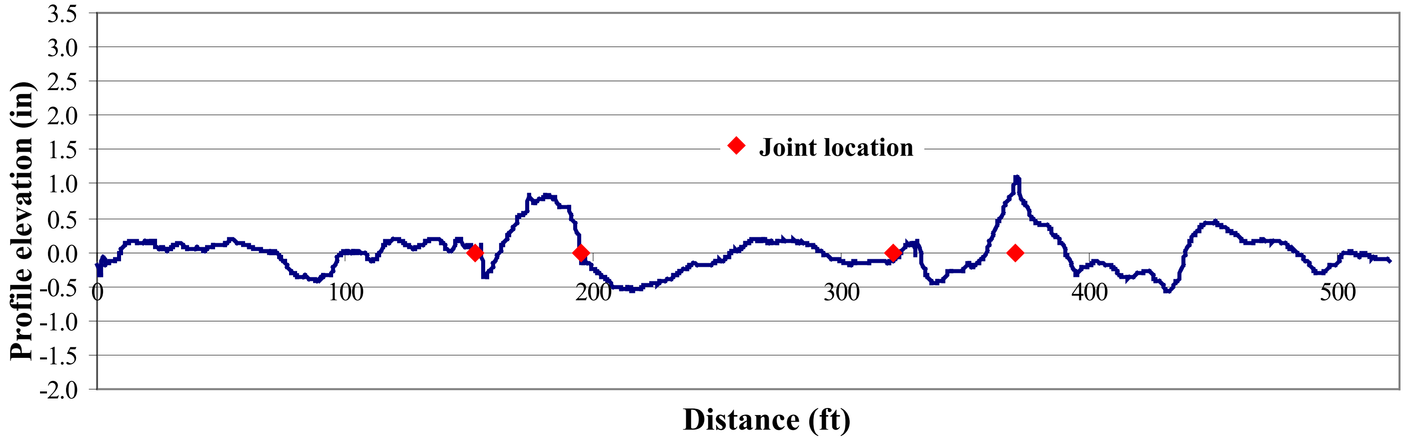
Bridge Structure Smoothness

IRI (in/mi)	RN
215	2.56

Rear Existing Pavement

IRI (in/mi)	RN
149	3.17

Bridge # 069-0060



Facility Carried: I 72 EB

Feature Crossed: Spring Creek

Number of Spans: 3

Longest Span: 49.0 ft (14.9 m)

Total Length: 138.0 ft (42.1 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Sag Curve

Total Test Section Smoothness

IRI (in/mi)	RN
192	2.47
203	2.49

Front Existing Pavement

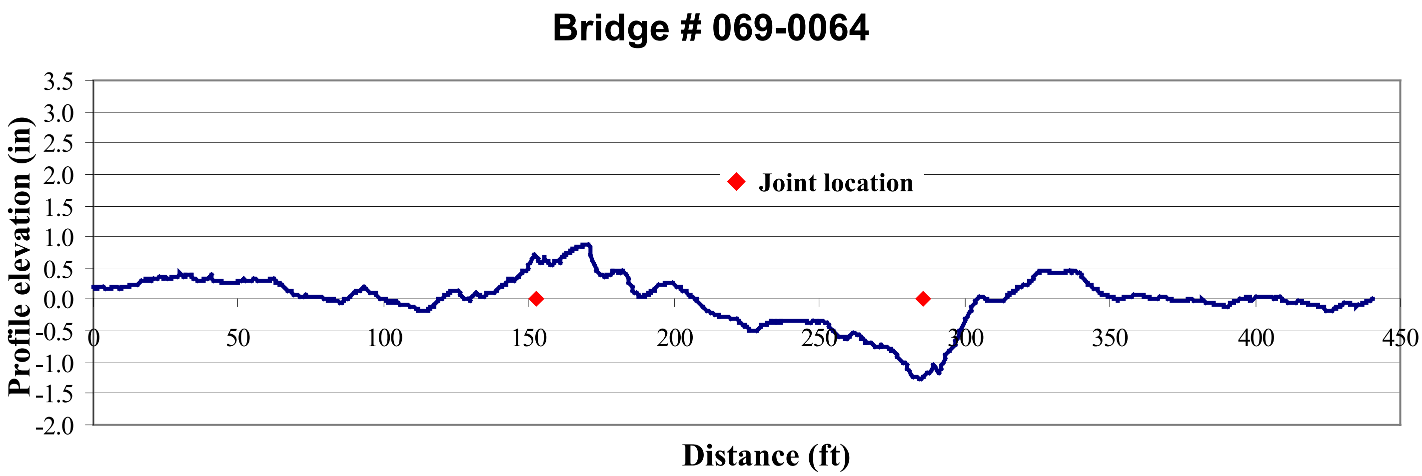
IRI (in/mi)	RN
166	2.75

Bridge Structure Smoothness

IRI (in/mi)	RN
198	2.22

Rear Existing Pavement

IRI (in/mi)	RN
180	2.82



Facility Carried: IL 123

Feature Crossed:
N. Fk. Mauvaise Terre

Number of Spans: 1

Longest Span: 77.0 ft (23.5 m)

Total Length: 79.7 ft (24.3 m)

Type of Beams: Steel

Skew: 25°

Profile: Downhill Grade

Total Test Section Smoothness

IRI (in/mi)	RN
143	3.08
134	3.15

Front Existing Pavement

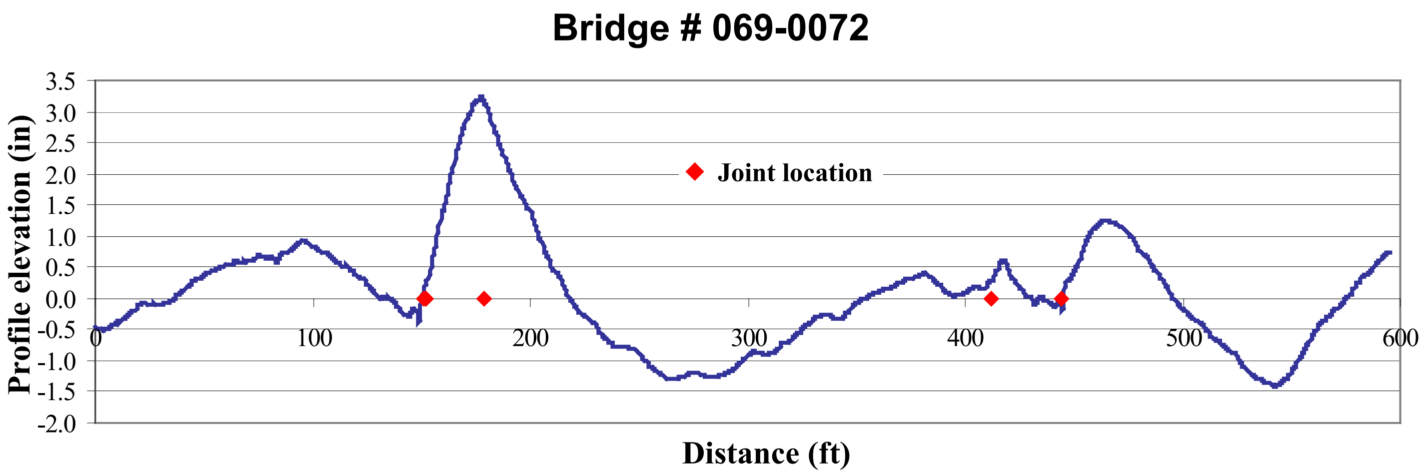
IRI (in/mi)	RN
106	3.39

Bridge Structure Smoothness

IRI (in/mi)	RN
175	2.72

Rear Existing Pavement

IRI (in/mi)	RN
129	3.21



Facility Carried: TR 96

Feature Crossed: US 67

Number of Spans: 2

Longest Span: 127.1 ft (38.7 m)

Total Length: 237.2 ft (72.3 m)

Type of Beams: PPC (Bulb "T")

Skew: 12°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
169	3.14
143	3.22

Front Existing Pavement

IRI (in/mi)	RN
99	3.00

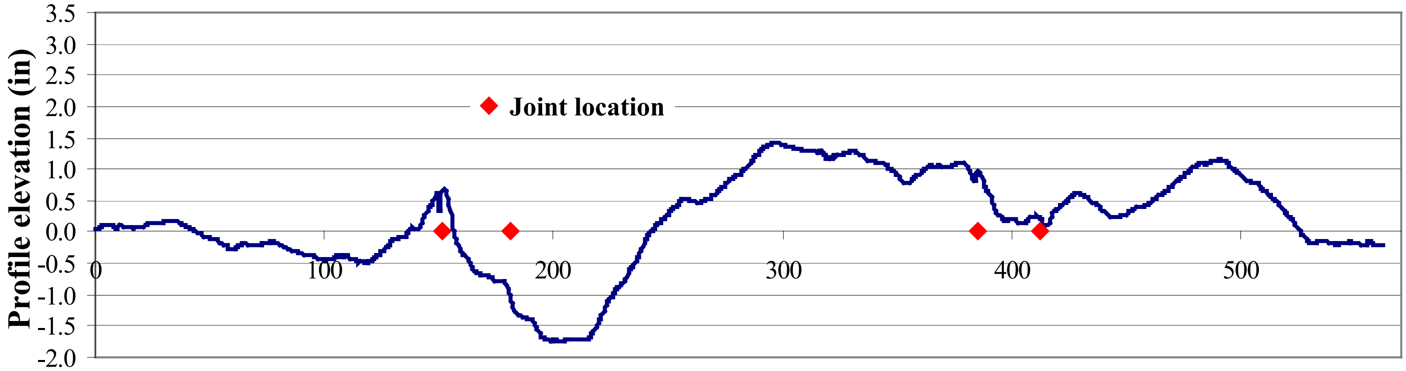
Bridge Structure Smoothness

IRI (in/mi)	RN
171	3.25

Rear Existing Pavement

IRI (in/mi)	RN
165	3.00

Bridge # 069-0077



Facility Carried: TR 157

Feature Crossed: US 67

Number of Spans: 2

Longest Span: 100.7 ft (30.7 m)

Total Length: 205.4 ft (62.6 m)

Type of Beams: PPC (I-Beam)

Skew: 0°

Profile: Slight Grade

Total Test Section Smoothness

IRI (in/mi)	RN
145	3.01
147	2.99

Front Existing Pavement

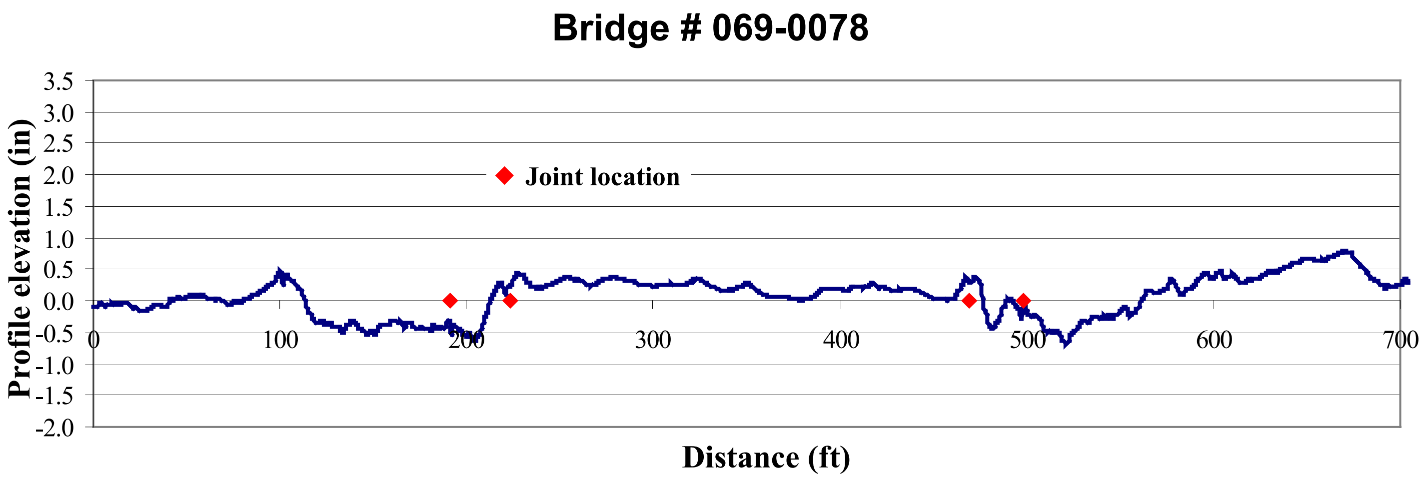
IRI (in/mi)	RN
89	3.15

Bridge Structure Smoothness

IRI (in/mi)	RN
179	2.73

Rear Existing Pavement

IRI (in/mi)	RN
117	3.78



Facility Carried:
Morton Avenue (Old US 36)

Feature Crossed: US 67

Number of Spans: 2

Longest Span: 128.4 ft (39.1 m)

Total Length: 247.7 ft (75.5 m)

Type of Beams: PPC

Skew: 21°

Profile: Slight Grade

Total Test Section Smoothness

IRI (in/mi)	RN
138	2.96
123	2.95

Front Existing Pavement

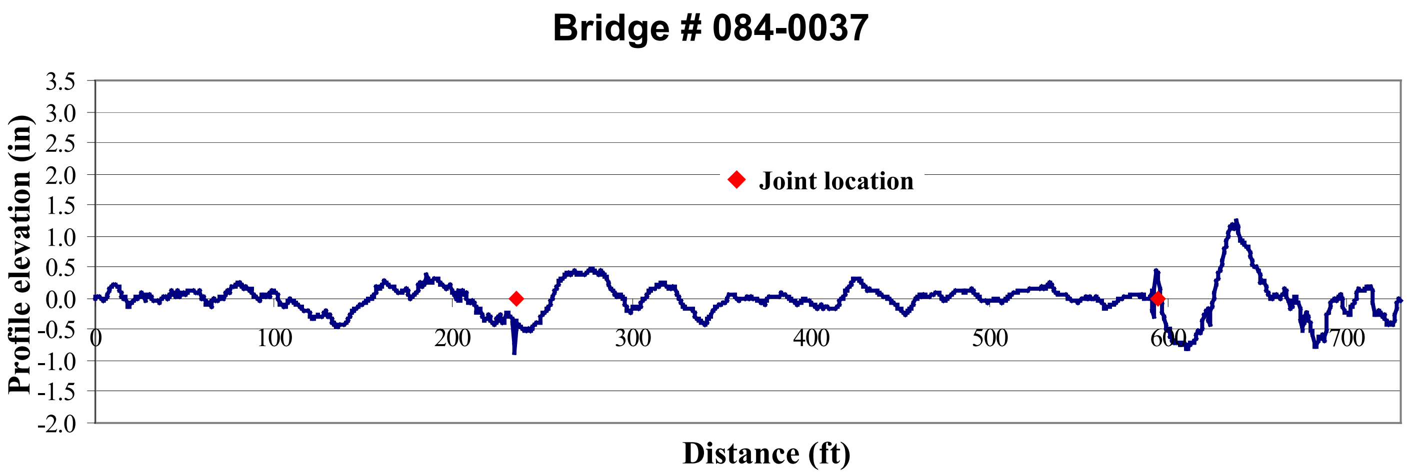
IRI (in/mi)	RN
128	3.12

Bridge Structure Smoothness

IRI (in/mi)	RN
138	2.85

Rear Existing Pavement

IRI (in/mi)	RN
139	3.14



Facility Carried:
11th Street/Hazel Dell

Feature Crossed: I 55 & I 72

Number of Spans: 2

Longest Span: 177.9 ft (54.2 m)

Total Length: 360.9 ft (110.0 m)

Type of Beams: Steel Continuous

Skew: 5°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
224	1.93
237	0.86

Front Existing Pavement

IRI (in/mi)	RN
162	2.66

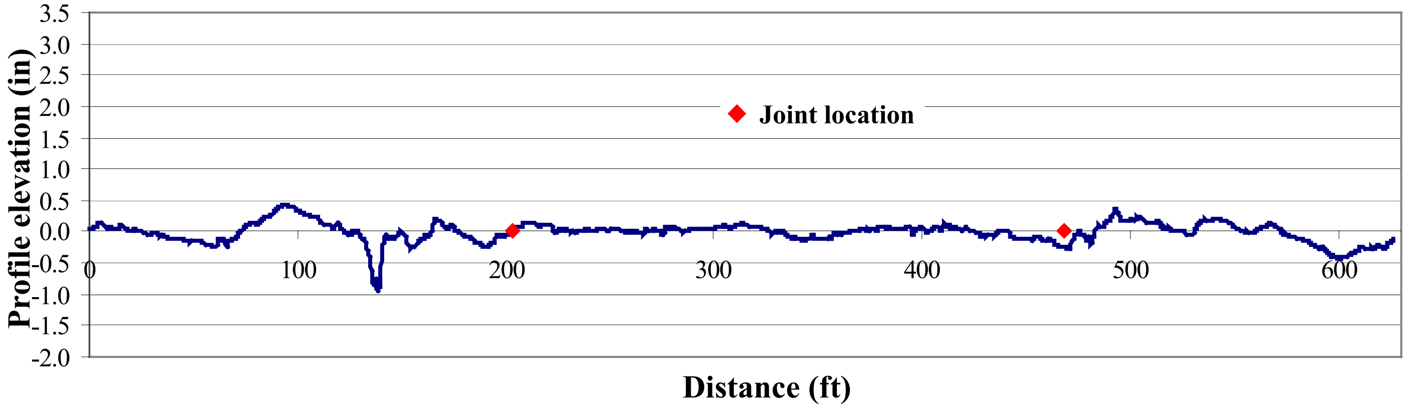
Bridge Structure Smoothness

IRI (in/mi)	RN
158	2.46

Rear Existing Pavement

IRI (in/mi)	RN
490	0.96

Bridge # 084-0078



Facility Carried: I 72/US 36 EB

Feature Crossed: I 55 SB

Number of Spans: 3

Longest Span: 153.0 ft (46.6 m)

Total Length: 347.0 ft (105.8 m)

Type of Beams: Steel Continuous

Skew: 62°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
131	2.76
147	2.84

Front Existing Pavement

IRI (in/mi)	RN
181	2.02

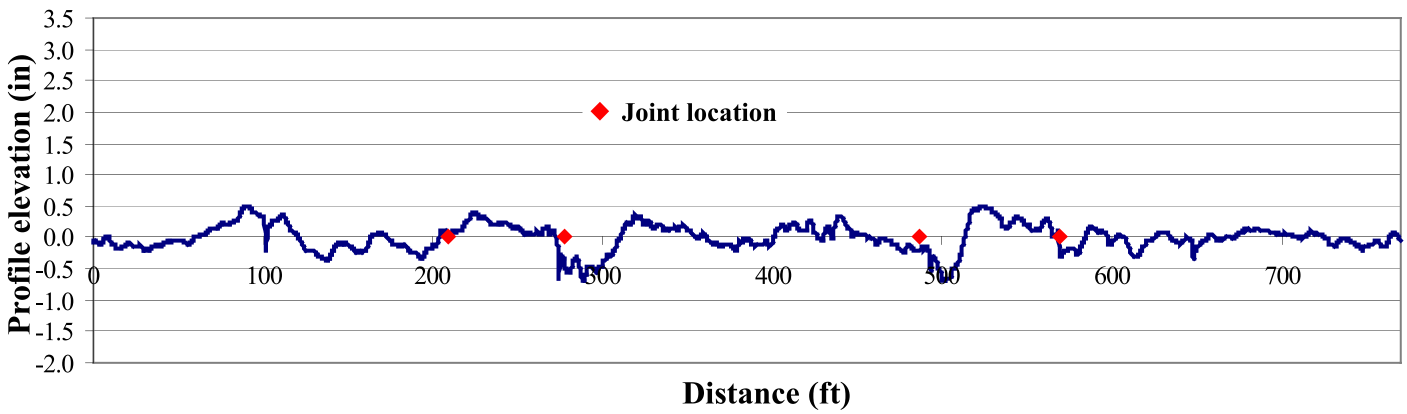
Bridge Structure Smoothness

IRI (in/mi)	RN
114	3.13

Rear Existing Pavement

IRI (in/mi)	RN
96	3.61

Bridge # 084-0127



Facility Carried: I 72/US 36 EB

Feature Crossed: N&W RR

Number of Spans: 3

Longest Span: 84.0 ft (25.6 m)

Total Length: 224.0 ft (68.3 m)

Type of Beams: Steel Continuous

Skew: 50°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
194	2.31
198	2.18

Front Existing Pavement

IRI (in/mi)	RN
163	2.14

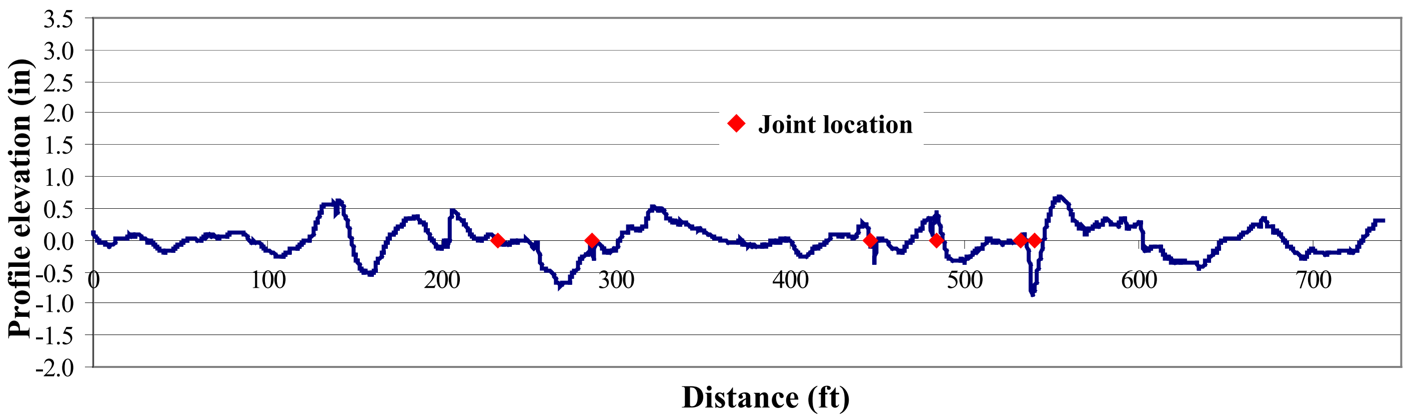
Bridge Structure Smoothness

IRI (in/mi)	RN
222	2.21

Rear Existing Pavement

IRI (in/mi)	RN
128	3.01

Bridge # 084-0149



Facility Carried: I 72/US 36 EB

Feature Crossed:
IL 54 & FAS 1613

Number of Spans: 2

Longest Span: 80.0 ft (24.4 m)

Total Length: 232.0 ft (70.7 m)

Type of Beams: Steel Continuous

Skew: 47°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
199	2.36
210	2.19

Front Existing Pavement

IRI (in/mi)	RN
141	3.17

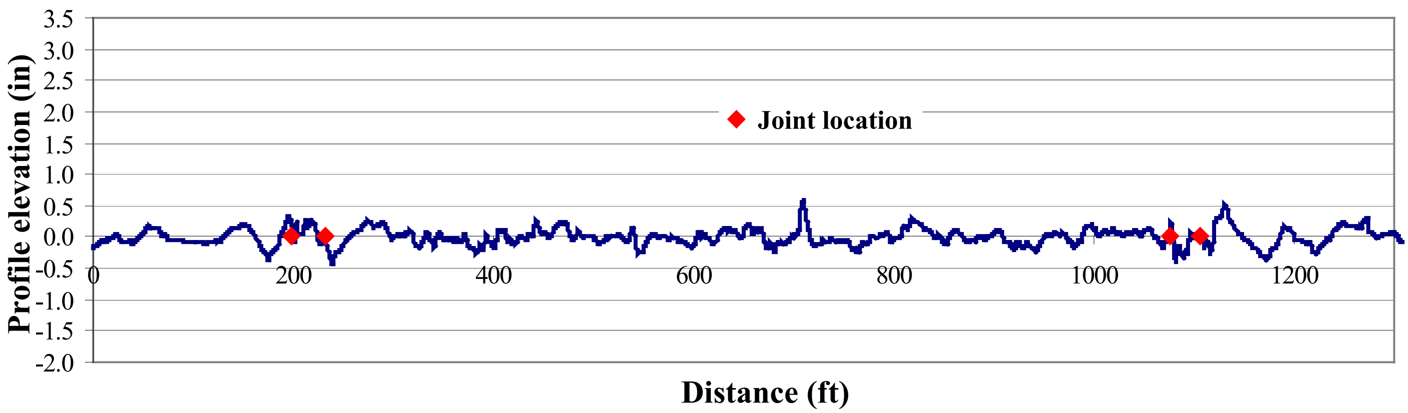
Bridge Structure Smoothness

IRI (in/mi)	RN
203	2.08

Rear Existing Pavement

IRI (in/mi)	RN
192	2.72

Bridge # 084-0205



Facility Carried: IL 54

Feature Crossed: Sangamon River

Number of Spans: 5

Longest Span: 185.0 ft (56.4 m)

Total Length: 852.6 ft (259.9 m)

Type of Beams: Steel Continuous

Skew: 0°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
155	2.90
138	2.87

Front Existing Pavement

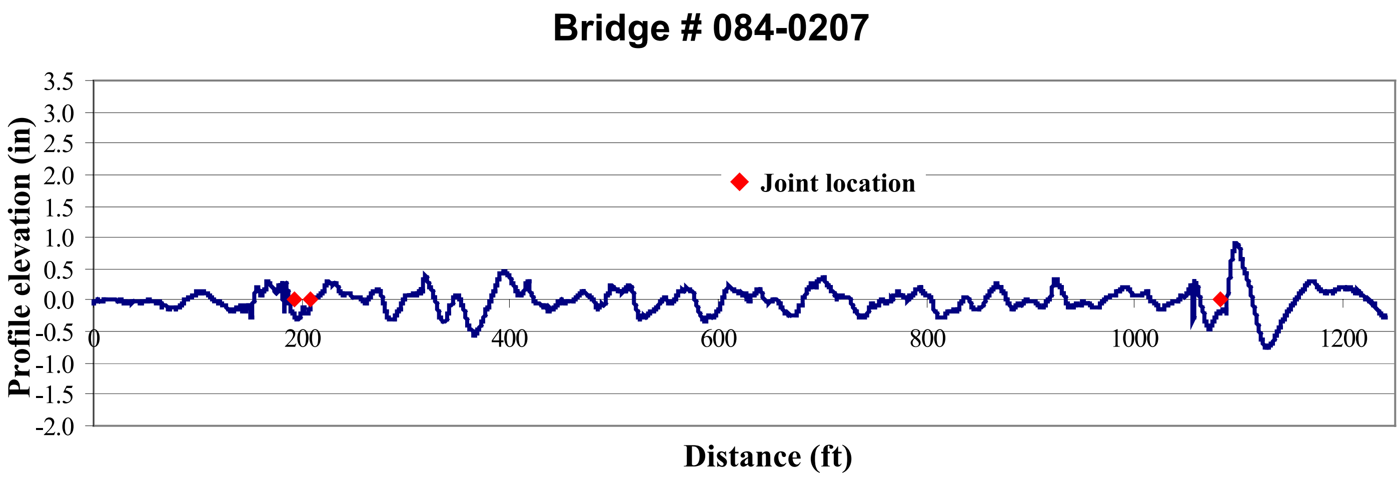
IRI (in/mi)	RN
86	3.81

Bridge Structure Smoothness

IRI (in/mi)	RN
169	2.77

Rear Existing Pavement

IRI (in/mi)	RN
159	3.00



Facility Carried: IL 29

Feature Crossed:
Sangamon River

Number of Spans: 4

Longest Span: 270.0 ft (82.3 m)

Total Length: 875.7 ft (266.9 m)

Type of Beams: Steel Girder

Skew: 0°

Profile: Vertical Curve

Total Test Section Smoothness

IRI (in/mi)	RN
156	2.65
171	1.96

Front Existing Pavement

IRI (in/mi)	RN
69	3.86

Bridge Structure Smoothness

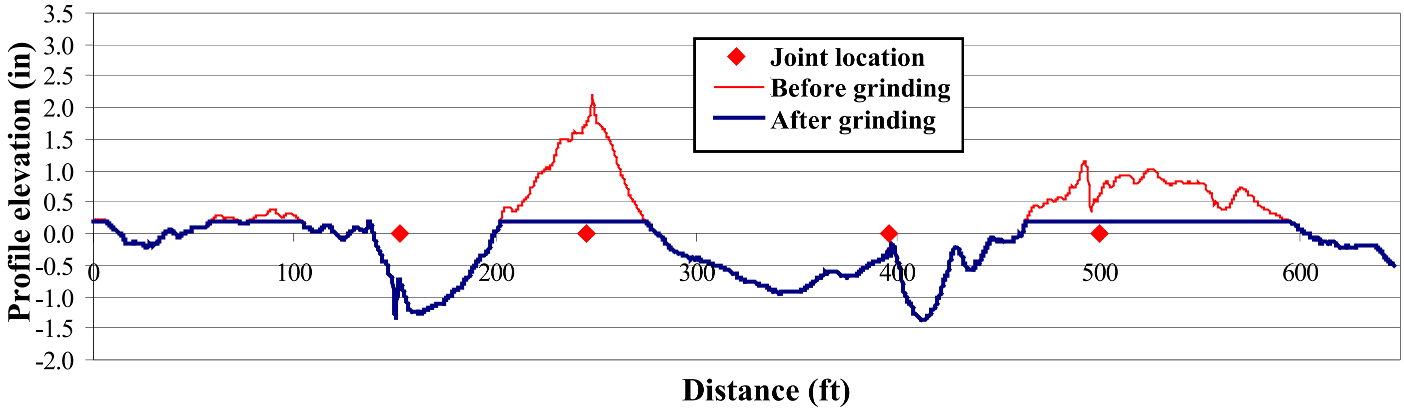
IRI (in/mi)	RN
158	2.47

Rear Existing Pavement

IRI (in/mi)	RN
187	3.31

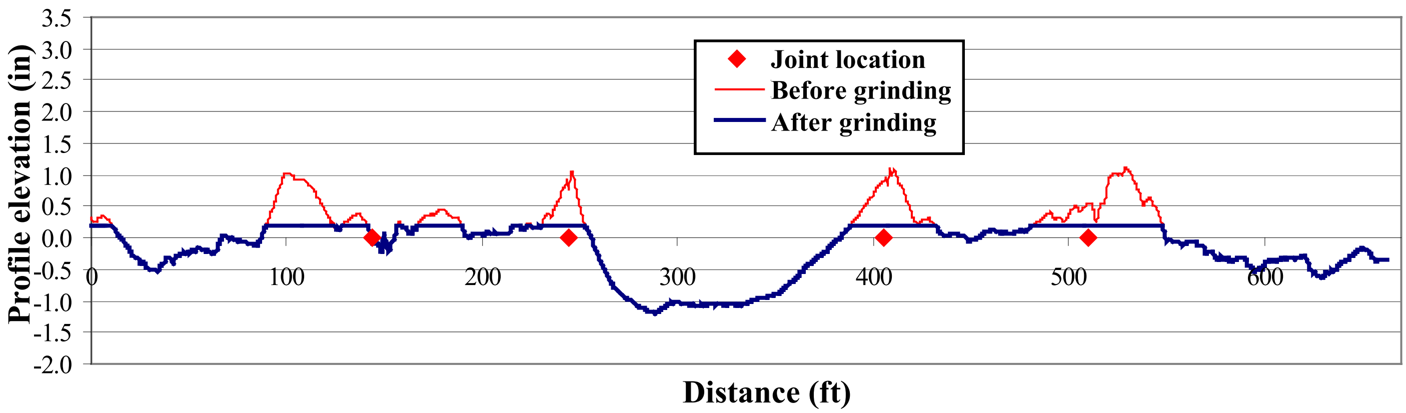
Appendix G – Grinding Simulation

Bridge # 069-0035



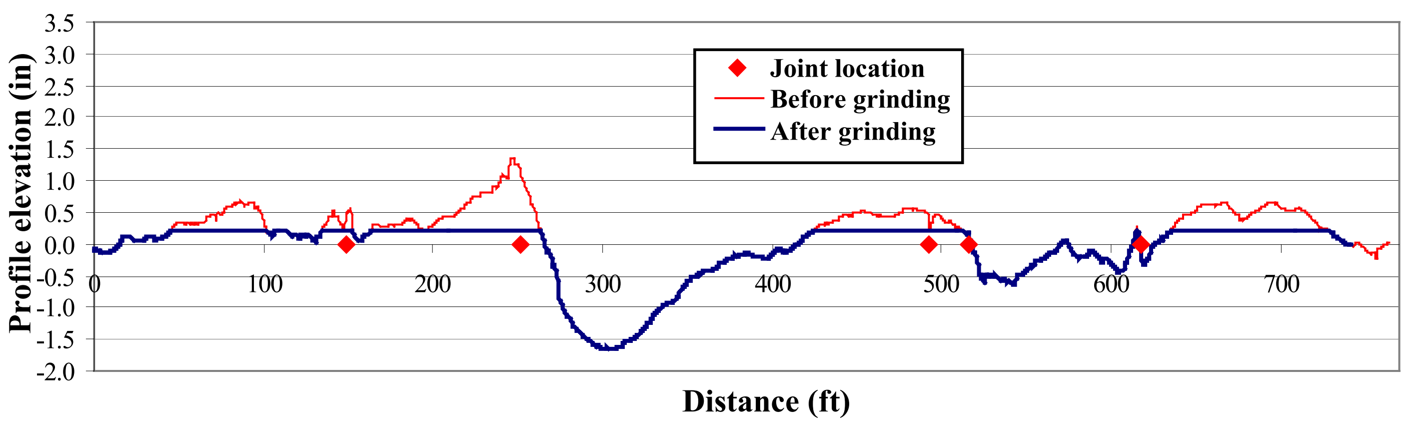
Before IRI = 193 RN = 2.30 After IRI = 123 RN = 2.77

Bridge # 069-0039



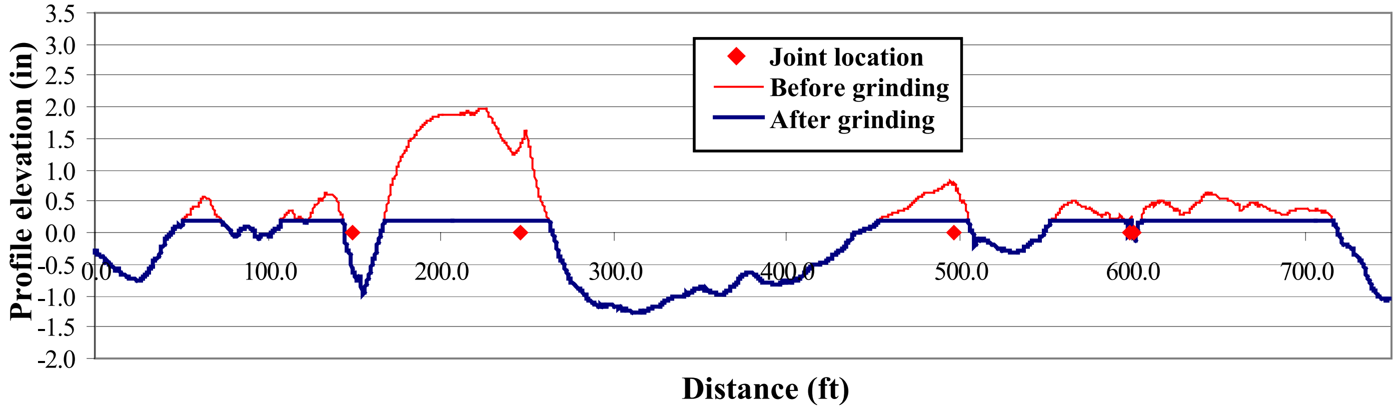
Before IRI = 183 RN = 2.61 After IRI = 104 RN = 3.2

Bridge # 069-0040



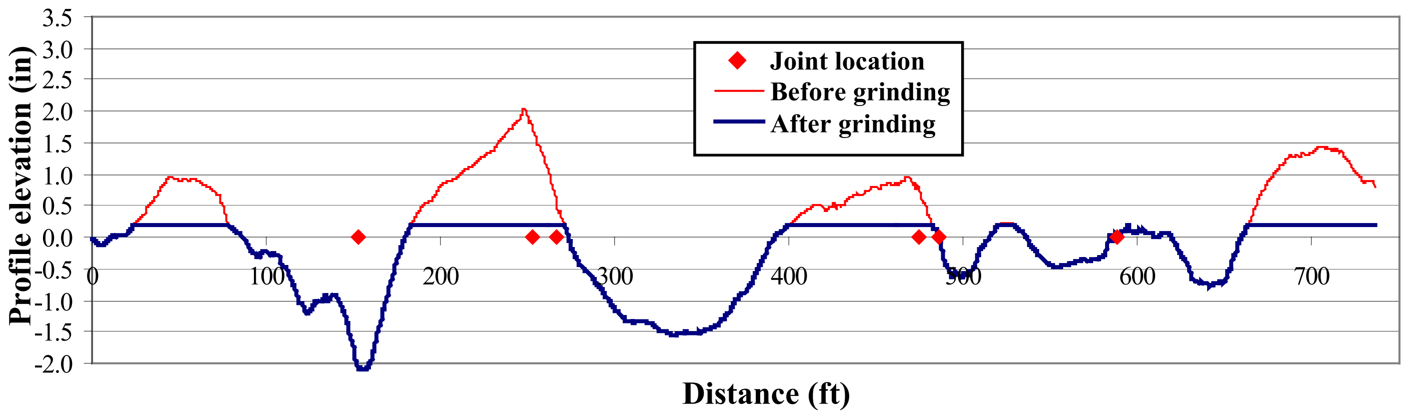
Before IRI = 135 RN = 2.88 After IRI = 83 RN = 3.38

Bridge # 069-0043



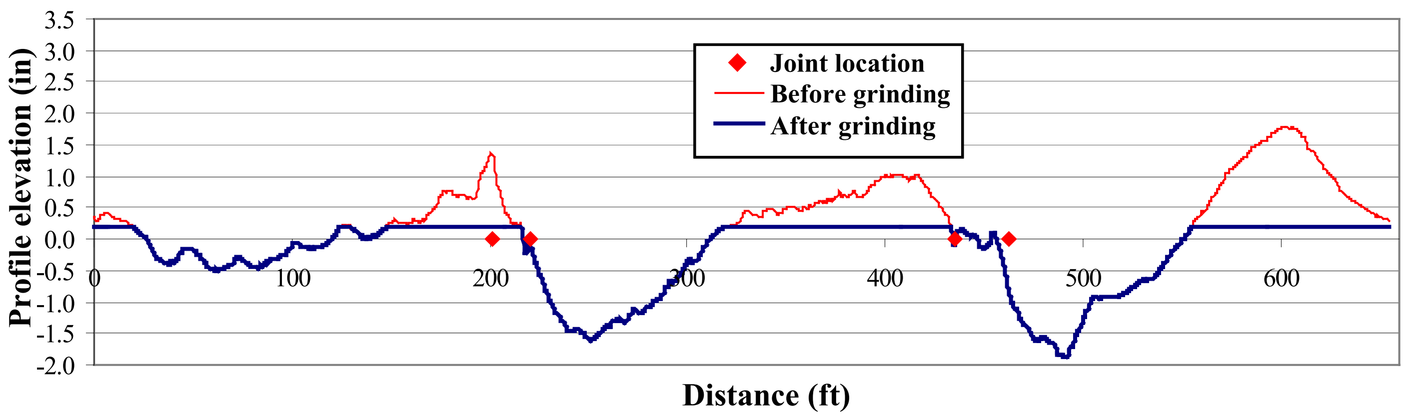
Before IRI = 159 RN = 2.92 After IRI = 107 RN = 3.22

Bridge # 069-0048



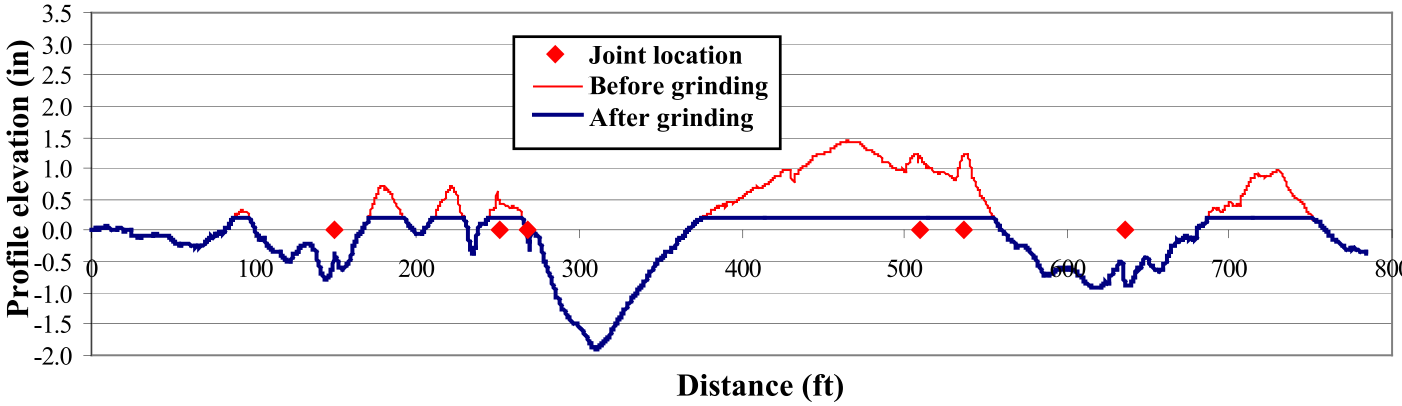
Before IRI = 165 RN = 3.34 After IRI = 140 RN = 3.57

Bridge # 069-0052



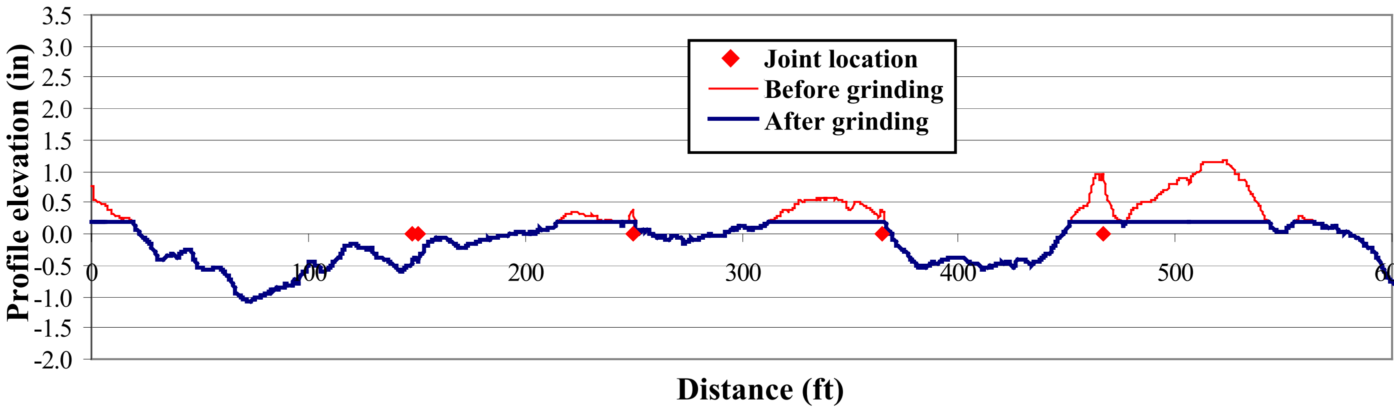
Before IRI = 162 RN = 2.76 After IRI = 116 RN = 3.17

Bridge # 069-0055



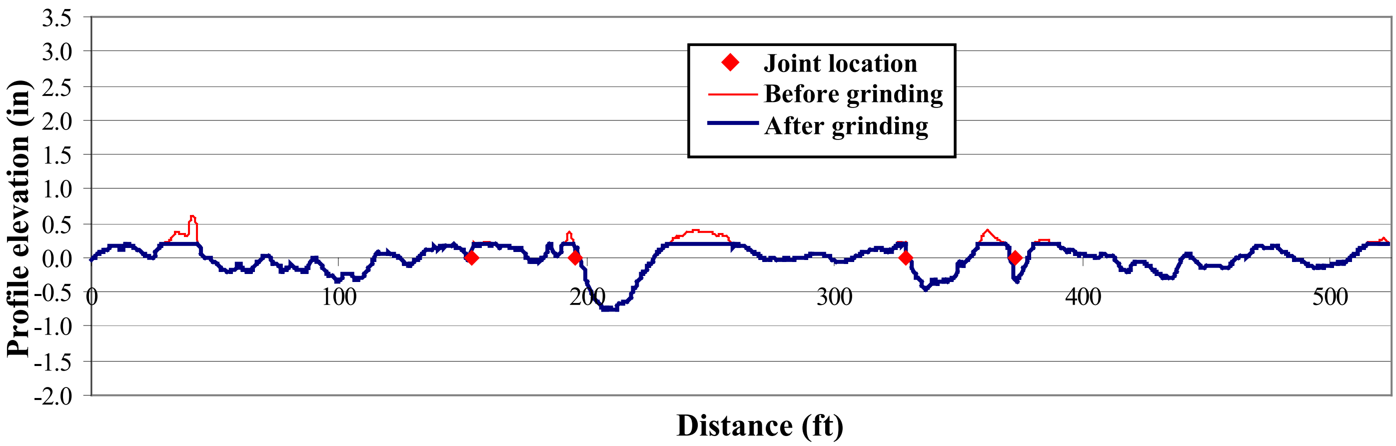
Before IRI = 166 RN = 2.76 After IRI = 114 RN = 3.11

Bridge # 069-0057



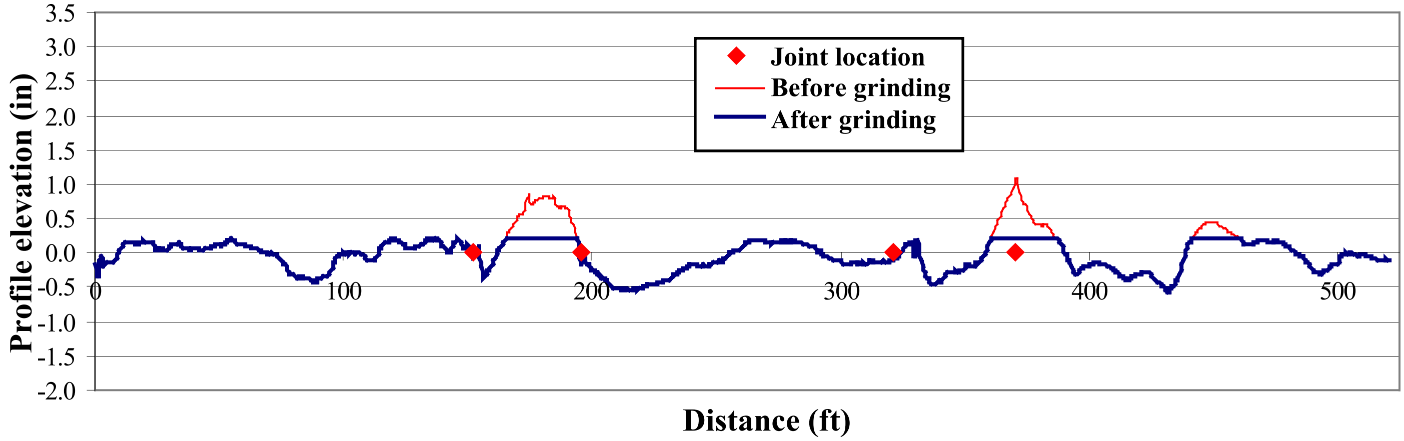
Before IRI = 158 RN = 2.89 After IRI = 103 RN = 3.43

Bridge # 069-0059



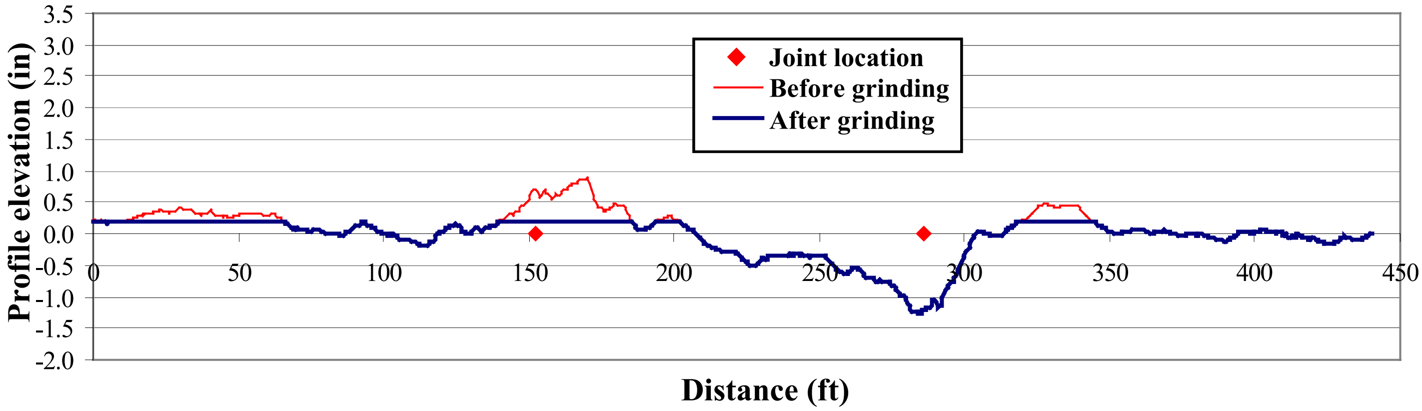
Before IRI = 196 RN = 2.62 After IRI = 173 RN = 2.85

Bridge # 069-0060



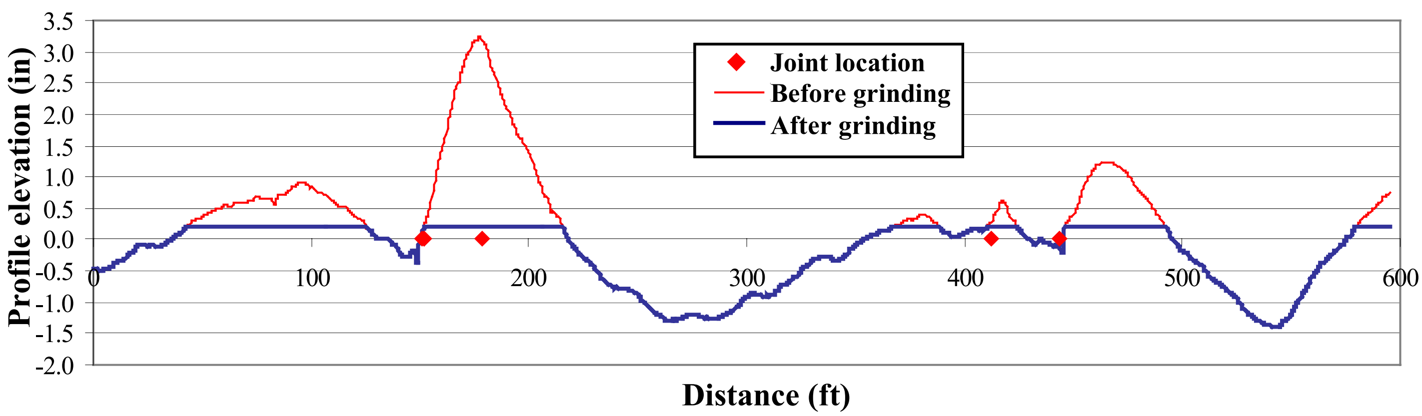
Before IRI = 192 RN = 2.47 After IRI = 158 RN = 2.60

Bridge # 069-0064



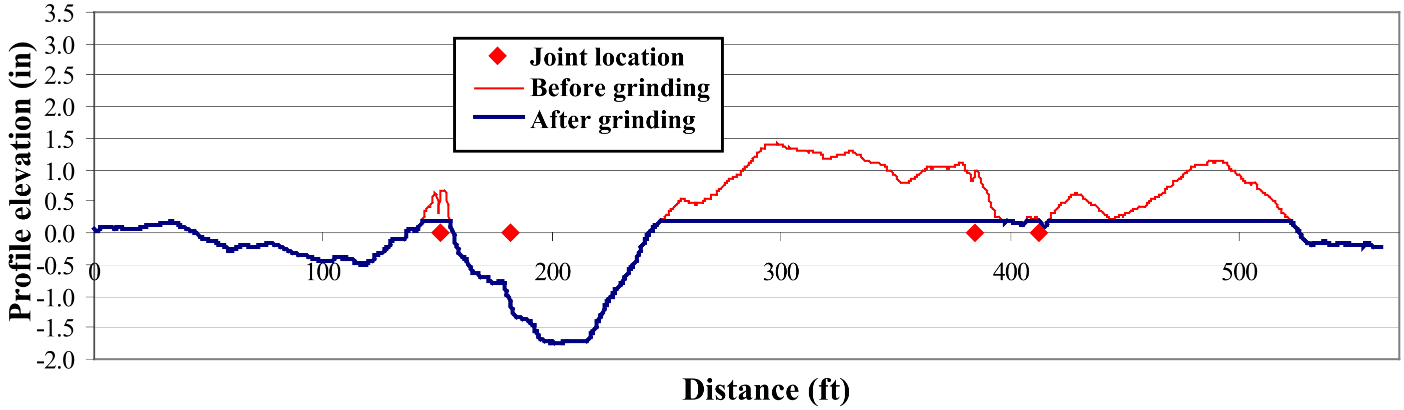
Before IRI = 143 RN = 3.08 After IRI = 107 RN = 3.48

Bridge # 069-0072



Before IRI = 169 RN = 3.14 After IRI = 90.6 RN = 3.32

Bridge # 069-0077



Before IRI = 145 RN = 3.01 After IRI = 80.2 RN = 3.74

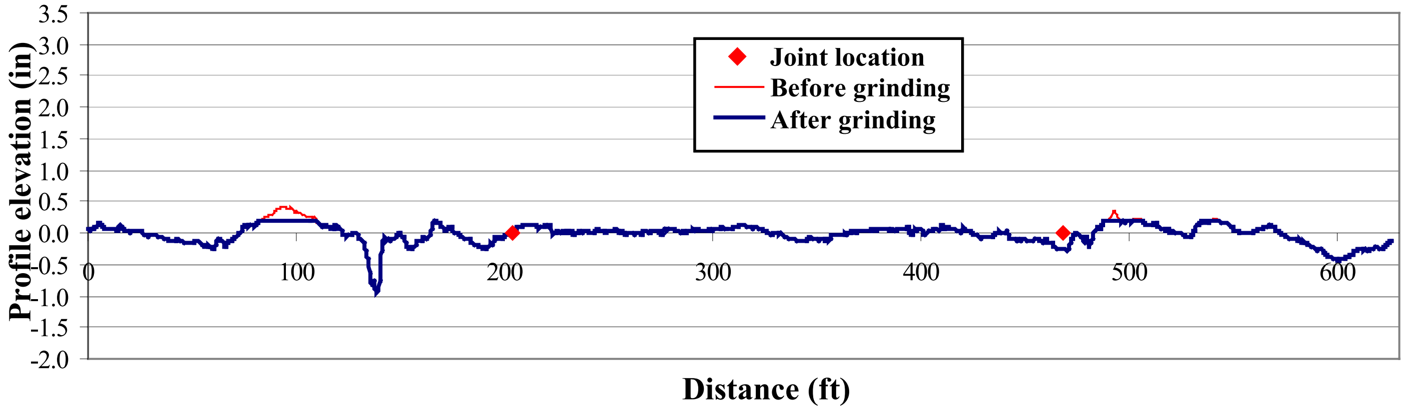
Bridge # 069-0078

Before IRI = 138 RN = 2.96 After IRI = 97.8 RN = 3.23

Bridge # 084-0037

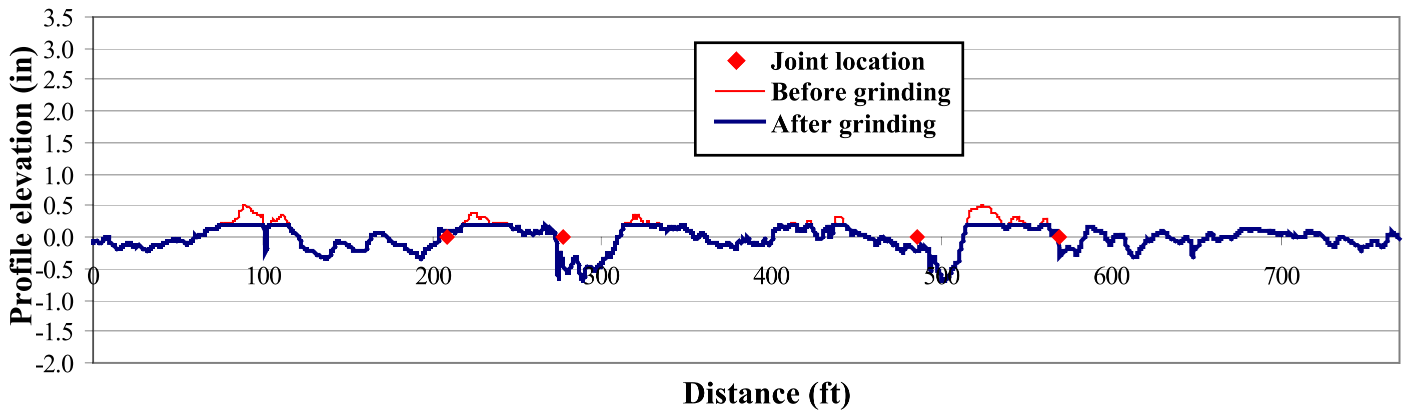
Before IRI = 224 RN = 1.93 After IRI = 201 RN = 2.06

Bridge # 084-0078



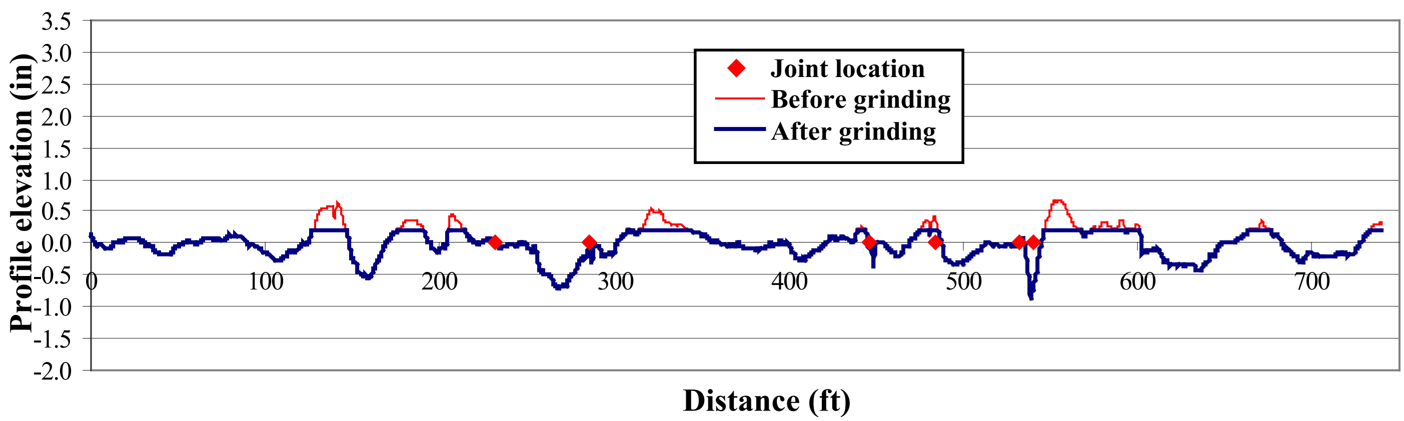
Before IRI = 131 RN = 2.76 After IRI = 126 RN = 2.79

Bridge # 084-0127



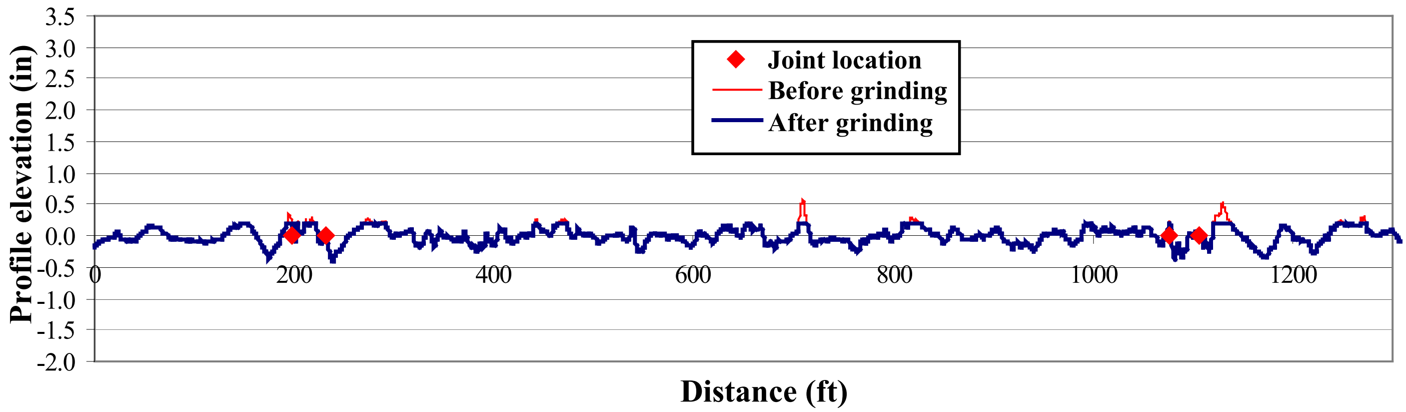
Before IRI = 194 RN = 2.31 After IRI = 174 RN = 2.40

Bridge # 084-0149



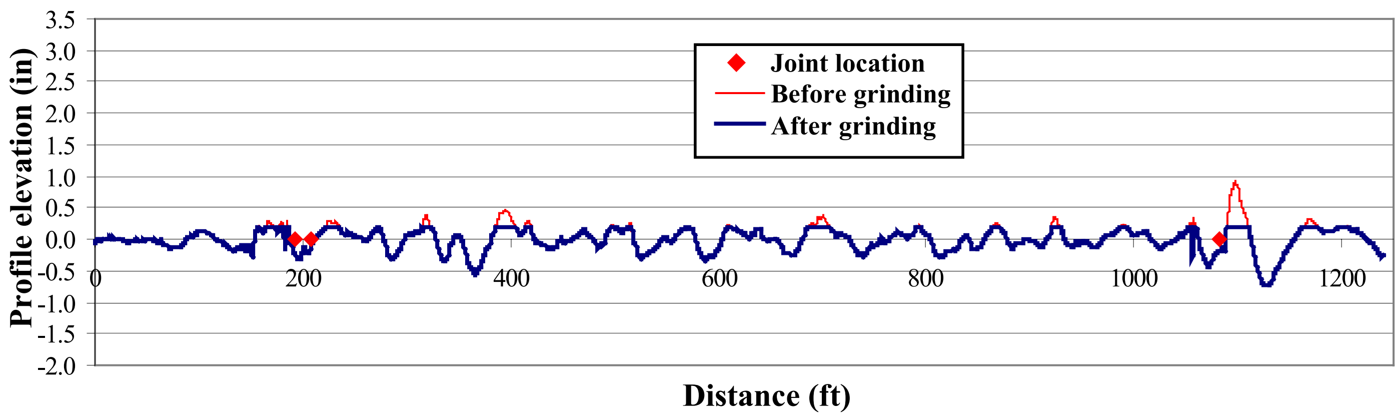
Before IRI = 199 RN = 2.36 After IRI = 163 RN = 2.56

Bridge # 084-0205



Before IRI = 155 RN = 2.90 After IRI = 144 RN = 3.01

Bridge # 084-0207



Before IRI = 156 RN = 2.65 After IRI = 139 RN = 2.85

Appendix H – IRI Before and After Grinding for the Right Wheel Path Considering the Total Section

IRI Before and After Grinding for the Right Wheel Path Considering the Total Section

Bridge	IRI (in/mi)	
	Before grinding	After grinding
069-0035	193	123
069-0039	183	104
069-0040	135	83
069-0043	159	107
069-0048	165	140
069-0052	162	116
069-0055	166	114
069-0057	158	103
069-0059	196	173
069-0060	192	158
069-0064	143	107
069-0072	169	91
069-0077	145	81
069-0078	138	98
084-0037	224	201
084-0078	131	126
084-0127	194	174
084-0149	199	163
084-0205	155	144
084-0207	156	139
Min	**131**	**81**
Max	**224**	**201**
Average	**168**	**127**
Standard deviation	**25**	**33**

Appendix I – ACPA Database

Smoothness Specification - Measuring Equipment Used and Roughness index

State	Smoothness measuring equipment	Roughness index
AL		
AK		
AZ	CA profilograph	Profile Index (in/mile)
AR	CA profilograph	Profile Index (in/mile)
CA	CA profilograph	Profile Index (in/mile)
CO	CA profilograph	Profile Index (in/mile)
CT	CA profilograph	Profile Index (in/mile)
DE	CA profilograph	Profile Index (in/mile)
FL	CA profilograph	Profile Index (in/mile)
GA	Rainhart profilograph	Profile Index (in/mile)
HI	CA profilograph, 12-ft straightedge	Profile Index (in/mile)
ID	CA profilograph 10-ft straightedge	Profile Index (in/0.1 mile)
IL	CA profilograph	IRI
IN	CA profilograph, 10-ft straightedge	Profile Index (in/0.1 mile)
IA	CA profilograph	Profile Index (in/mile)
KS	CA profilograph, others	Profile Index (in/mile)
KY	noncontact profilometer	IRI
LA	CA profilograph	Profile Index (in/mile)
ME	10-ft straightedge	
MD	CA profilograph	Profile Index (in/mile)
MA		
MI	CA profilograph, GM Profilometer	Ride Quality Index
MN	CA profilograph	Profile Index (in/mile)
MS	CA profilograph	Profile Index (in/mile)
MO	CA profilograph	Profile Index (in/mile)
MT	CA profilograph	Profile Index (in/mile)

Smoothness Specification - Measuring Equipment Used and Roughness index (Continued)

State	Smoothness measuring equipment	Roughness index
NE	CA profilograph	Profile Index (in/mile)
NV	CA profilograph	
NH		
NJ	10-ft straightedge	none
NM	CA profilograph	Profile Index (in/mile)
NY	CA profilograph	IRI
NC	Rainhart profilograph	Profile Index (in/mile)
ND	CA profilograph	inch / 0.10 mile
OH	CA profilograph, 10-ft straightedge	Profile Index (in/mile)
OK	CA profilograph, straightedge	Profile Index (in/mile)
OR	CA profilograph	Profile Index (in/mile)
PA	CA profilograph, others	Profile Index (in/mile)
PR	CA profilograph	Profile Index (in/mile)
RI	10-ft straightedge	
SC	Rainhart profilograph	Profile Index (in/mile)
SD	CA profilograph	Profile Index (in/mile)
TN	Rainhart profilograph	Profile Index (in/mile)
TX	CA profilograph, others	Profile Index (in/mile)
UT	CA profilograph, 10-ft straightedge	Profile Index (in/mile)
VT		
VA		
WA	CA profilograph	Profile Index (in/mile), IRI
WV	Mays Meter	Mays ride number
WI	CA profilograph	Profile Index (in/mile)
WY	CA profilograph	Profile Index (in/mile)

Smoothness Specification - Blanking Band and Must-Grind Bump Requirement

State	Blanking band width	Must grind bump
AL		
AK		
AZ	0.20	0.3 in / 25 ft
AR	0.10	0.3 in / 25 ft
CA	0.20	0.3 in / 25 ft
CO	0.20	0.4 in / 25 ft
CT	0.20	0.5 in / 25 ft
DE	0.20	0.3 in / 25 ft
FL	0.20	0.3 in / 25 ft
GA	0.10	> band by 0.2"
HI	0.20	0.3 in / 25 ft
ID	0.20	0.3 in / 25 ft
IL		0.3 in / 25 ft
IN	5 mm	0.3 in / 25 ft
IA	0.20	0.5 in / 25 ft
KS	0.00	0.3 in / 25 ft
KY		none
LA	0.20	0.3 in / 25 ft
ME		
MD	0.20	0.3 in / 25 ft
MA		
MI	0.20	0.3 in / 25 ft
MN	0.20	0.3 in / 25 ft
MS	0.20	0.3 in / 25 ft
MO	0.00	0.4 in / 25 ft
MT	0.20	0.3 in / 25 ft

Smoothness Specification - Blanking Band and Must-Grind Bump Requirement (Continued)

State	Blanking band width	Must grind bump
NE	0.20	0.3 in / 25 ft
NV		
NH		
NJ		0.125 in / 10 ft
NM	0.10	0.3 in / 25 ft
NY	0.20	0.5 in / 25 ft
NC	0.20	0.3 in / 25 ft
ND	0.20	0.3 in / 25 ft
OH	0.20	0.3 in / 25 ft
OK	0.20	0.4 in / 25 ft
OR	0.20	0.3 in / 25 ft
PA	0.00	0.4 in / 25 ft
PR	0.20	0.4 in / 25 ft
RI		0.1 in / 10 ft
SC	0.20	none
SD	0.00	0.3 in / 25 ft
TN	0.10	0.4 in / 25 ft
TX	0.20	0.3 in / 25 ft
UT	0.20	0.3 in / 25 ft
VT	0.20	
VA		
WA	0.30	10 mm / 0.1 km
WV		
WI	0.01	0.4 in / 25 ft
WY	0.20	0.3 in / 25 ft

Smoothness Specification - Measurement Requirements

State	Profile measurement location	Length of section evaluated	How profile index calculated	Acceptance measurement by
AL				
AK				
AZ	both wheel paths	0.1 mile	by hand or computer	State
AR	center of lane	0.1 mile	by hand or computer	contractor, State
CA	both wheel paths	0.1 mile	by hand or computer	contractor
CO	both wheel paths	0.1 mile	by hand or computer	State
CT	both wheel paths	1000 ft min	by hand	State
DE	both wheel paths	0.1 mile	computer	State
FL	both wheel paths	0.1 mile	computer	State
GA	outer wheelpath	0.25 mile	by hand	contractor
HI	both wheel paths	0.1 mile	by hand	State
ID	right wheel path	0.1 mile	by hand, computer	contractor
IL	center, outer	0.1 mile	digital scan	State, contractor
IN	outer wheel path	0.1 mile	by hand	contractor
IA	center of lane	0.1 mile	by hand, computer, digital scan	contractor
KS	both wheel paths	0.1 mile	computer, digital scan	contractor
KY	both wheel paths	1.5 km	computer	State
LA	both wheel paths	depends on lot	0 - 6 in / mile / lot	State
ME				
MD	outer wheel path	0.1 mile	computer	contractor
MA				
MI	outer wheel path	mile	by hand or computer	contractor
MN	center of lane	0.1 mile	computer, digital scan	contractor
MS	both wheel paths	0.1 mile	by hand or computer	contractor
MO	both wheel paths	0.1 mile	by hand or computer	contractor, State
MT	outer wheel path	0.1 mile	by hand or computer	State

Smoothness Specification - Measurement Requirements (Continued)

State	Profile measurement location	Length of section evaluated	How profile index calculated	Acceptance measurement by
NE	outer wheel path	0.1 mile	computer	contractor
NV				
NH				
NJ	center of lane			State
NM	both wheel paths	0.1 mile	by hand or computer	contractor
NY	both wheel paths	0.25 mile	by hand	contractor
NC	both wheel paths	600 ft	by hand	contractor
ND	outer wheel paths	0.1 mile	computer	State
OH	both wheel paths	0.1 mile	by hand or computer	contractor
OK	both wheel paths	0.1 mile	computer, digital scan	
OR	either wheelpath	0.1 mile	by hand or computer	contractor
PA	both wheel paths	0.1 mile	by hand, computer, digital scan	contractor
PR	outer wheel path	0.1 mile	computer	State
RI	random	random		State
SC	both wheel paths	0.25 mile	by hand	State
SD	both wheel paths	0.1 mile	computer	contractor
TN	both wheel paths	0.1 mile	by hand	State
TX	both wheel paths	0.1 mile	by hand	contractor, State
UT	outer wheel path	0.1 mile	computer	contractor
VT				
VA				
WA	right wheel path	all	computer	Contractor
WV	both wheel paths	0.1 mile	computer	State
WI	both wheel paths	0.1 mile	computer	Contractor
WY	both wheel paths	0.1 mile		State

Smoothness Specification - Pay Factors and Limits

State	Index range for 100% payment	Index for maximum incentive	Max incentive possible	Worst roughness index allowable	Acceptance measurement by
AL					
AK					
AZ	7 - 9				
AR	6-7 in/mile	2 in/mile or less	105% sq yd price	7 in/mile	
CA	5 - 7				
CO	7 - 12				
CT	10 - 12	0 - 6	106% cy unit price	18 - 20	92% cy unit price
DE		< 40 mm / km	$1.50 / m2	175 mm / km	
FL			103% sy unit price	7 in/mile	
GA				7 in/mile	
HI	7 - 10			10	70% sy unit price
ID					
IL	4.25 - 10	< 2.25	103% sy unit price	15	90% sy unit price
IN	30 mm / 1.6 km	< 13 mm / 1.6 km	103% sm unit price	30 mm / 1.6 km	
IA	3.1 - 7.0	0 - 1.0	$200-650 per segment	10.1	$100-300 per segment
KS	18 - 40, 25 - 65	6, 15	$1200, $1000 / 0.1 mile	25, 45	$750 per 0.1 mile
KY	3.55 - 4.04		103% sy unit price	3.45 - 3.49	98% sy unit price
LA				8 in / mile / lot	95% sy unit price
ME					
MD	4 - 12	< 2	105% sy unit price		90% sy unit price
MA					
MI	4 - 10	0	100% sy unit price	10	
MN	4 - 6	0 - 4	$/sy formula	6 - 8	$/sy formula
MS	< 7				
MO	18.1 -30	< 10	107% sy unit price	30	95% sy unit price
MT	6 - 10	< 6	$0.50 / sy	10 - 15	$1.00 / sy

Smoothness Specification - Pay Factors and Limits (Continued)

State	Index range for 100% payment	Index for maximum incentive	Max incentive possible	Worst roughness index allowable	Acceptance measurement by
NE	7 - 10	0 - 2	105% sy unit price	15	90% sy unit price
NV					
NH					
NJ					5% per lot
NM	4 - 7				
NY	5	0-1	105% sy unit price	12	to be determined
NC	4				
ND	0.3 to 0.5 / 0.1 mile	< 0.3 inch / 0.1 mile	$0.50 / sy	0.9 inch / 0.1 mile	unit price - $4.00/sy
OH	5 - 7	< 3	105% sy unit price	12	90% sy unit price
OK					
OR	5 - 7	2.5	101.5% sy unit price	7	
PA	< 36	< 18	107% sy unit price	36	100% sy unit price
PR	20 - 30		formula		formula
RI					
SC			100% sy unit price	10	
SD	25 - 35	< 10	104% sy unit price	40	98% sy unit price
TN	< 10			10, 15	
TX	4 - 6	< 1.5	$90 per 0.1 mile section	12	$140 per 0.1 mile section
UT	7		$1.00 / sy		60% sy unit price
VT					
VA					
WA	7	< 1	104% half mile section	7	98% half mile section
WV	< 100			100	
WI	19.1 - 32	< 10	$1.00 per foot per lane	45	$8300 per mile per lane
WY	6 - 7			7	

Incentive and Disincentives

State	Ride	Thickness	Strength
AL			
AK			
AZ			
AR	incentives	disincentives	disincentives
CA			
CO			
CT	both	both	no
DE	both	disincentives	no
FL	incentives	no	disincentives
GA	no	no	no
HI	disincentives	no	no
ID	both	both	no
IL	both	both	no
IN	yes	yes	yes
IA	both	both	no
KS	both	both	no
KY			
LA	disincentives	disincentives	disincentives
ME			
MD	both		
MA			
MI	incentives	disincentives	disincentives
MN	both	no	no
MS	disincentives	disincentives	no
MO	both	no	no
MT	both	both	both

Incentive and Disincentives (Continued)

State	Ride	Thickness	Strength
NE	both	disincentives	disincentives
NV			
NH			
NJ	both	both	both
NM			
NY	incentives	no	no
NC	no	both	both
ND	both	both	no
OH	both	disincentives	no
OK	both	both	disincentives
OR	incentives	disincentives	disincentives
PA	both	disincentives	disincentives
PR	both	disincentives	disincentives
RI			
SC	no	no	no
SD	both	no	no
TN	no		both
TX	both	disincentives	no
UT	both	disincentives	disincentives
VT			
VA			
WA	both	disincentives	no
WV			
WI	both	both	
WY			

Appendix J – Data used to develop a New Correlation Between IRI and PI

Data used to develop a New Correlation Between IRI and PI

Bridge #	Facility Carried	Length (ft)	Pass#	Length (ft)	IRI (in/mi)	PI (in/mi)	Length (ft)	IRI (in/mi)	PI (in/mi)	Length (ft)	IRI (in/mi)	PI (in/mi)
069-0035	I 72 EB	151.3	1		193	54.3						
			2		159	41.1						
069-0039	I 72 WB	168.0	1		183	50.5						
			2		169	39.8						
069-0040	I 72 EB	268.3	1		135	29.6						
			2		135	26.1						
069-0043	I 72 WB	252.0	1*		159	46.5						
			2*		162	46.1						
			3*		159	46.4						
			4*		163	45.3						
			5		155	41.2						
069-0048	I 72 EB	239.5	1		165	41.1						
			2		159	39.4						
069-0052	IL 123	252.0	1*	0 - 528.0	178	56.3	528.0 - 654.0	92	9.2			
			2*	0 - 528.0	181	50.5	528.0 - 653.5	96	6.9			
			3	0 - 655.5	178	44.4						
069-0055	I 72 WB	286.8	1		166	47.2						
			2		164	47.7						
069-0057	I 72 WB	118.0	1	0 - 528.0	156	40.4	528.0 - 616.5	176	49.6			
			2	0 - 528.0	169	46.3	528.0 - 619.0	187	48.3			
069-0059	I 72 WB	138.0	1		196	54.5						
			2		165	46.2						
069-0060	I 72 EB	138.0	1		192	56.0						
			2		203	49.1						
069-0072	TR 96	237.2	1		169	44.8						
			2		143	32.4						

* Repeated Right Wheel Path

Data used to develop a New Correlation Between IRI and PI (Continued)

Bridge #	Facility Carried	Length (ft)	Pass#	Length (ft)	IRI (in/mi)	PI (in/mi)	Length (ft)	IRI (in/mi)	PI (in/mi)	Length (ft)	IRI (in/mi)	PI (in/mi)
069-0077	TR 157	205.4	1*		145	39.4						
			2*		144	36.2						
			3*		147	36.6						
			4*		145	36.0						
			5+		147	35.9						
			6+		145	35.3						
			7+		145	38.6						
			8+		149	38.5						
069-0078	Morton Avenue (Old US 36)	247.7	1		138	30.5						
			2		123	22.7						
084-0037	11th Street/Hazel Dell	360.9	1	0 - 528.0	167	37.4	528.0 - 729.5	375	122.9			
			2	0 - 528.0	191	44.1	528.0 - 743.0	350	131.9			
084-0078	I 72/US 36 EB	347.0	1	0 - 528.0	135	24.4	528.0 - 626.5	104	18.8			
			2	0 - 528.0	150	35.7	528.0 - 655.0	133	28.5			
084-0127	I 72/US 36 EB	224.0	1	0 - 528.0	198	46.9	528.0 - 770.0	186	31.4			
			2	0 - 528.0	192	50.8	528.0 - 768.5	210	54.9			
084-0149	I 72/US 36 EB	232.0	1*	0 - 528.0	191	60.1	528.0 - 740.0	219	67.1			
			2*	0 - 528.0	195	58.8	528.0 - 739.5	222	66.8			
			3	0 - 528.0	201	65.8	528.0 - 738.5	233	74.0			
084-0205	IL 54	852.6	1	0 - 528.0	141	21.8	528.0 - 1056.0	150	28.7	1056.0 - 1310.0	196	49.4
			2	0 - 528.0	126	26.6	528.0 - 1056.0	141	25.7	1056.0 - 1313.0	159	28.3
084-0207	IL 29	875.7	1	0 - 528.0	160	42.8	528.0 - 1056.0	123	31.7	1056.0 - 1241.0	236	59.1
			2	0 - 528.0	204	58.9	528.0 - 1056.0	121	31.0	1056.0 - 1236.0	219	57.2
069-0073	New Bridge		1	0 - 528.0	161	38.9	528.0 - 640.5	152	53.5			
			2	0 - 528.0	53	1.5	528.0 - 1056.0	153	34.1			

* Repeated Right Wheel Path

\+ Repeated Left Wheel Path

Appendix K – Draft of the Preliminary Bridge Smoothness Specification for Illinois

Draft of the Preliminary Bridge Smoothness Specification for Illinois

a. Description. This section describes the testing procedure for determining acceptance and price adjustments regarding bridge deck smoothness.

b. Testing procedure. Finished bridge floors shall be tested using a Lightweight Profiler in accordance with ASTM E 950-98 (Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference). The Contractor shall remove all objects and debris before starting the testing procedure. The pavement profiles shall be taken 3 ft from and parallel to each outside edge for all lanes. The profile test shall begin 50 ft before and after the bridge approach pavement, continue across the bridge deck, and concluding 50 ft beyond. The testing shall start as soon as the concrete has enough strength to support the device. After the Engineer accepts the initial pavement smoothness, daily profiles will be run during the next working day following placement of concrete. If the contract does not require the Contractor to furnish a lightweight profiler, the Department will furnish it.

c. Smoothness evaluation. The International Roughness Index (IRI) will be determined for each 0.05 mile of the day's paving. The Engineer must have access to the data as soon as the test is performed. If an IRI value of more than 150 in/mi is obtained, corrections will be required.

d. Corrective actions. The identification of the areas where corrective actions are necessary will be based on the profile trace and IRI statistics. At the Contractor's expense, deviations (bumps or dips) greater than 0.4 in shall be corrected by grinding or cutting, regardless of the smoothness index for the section. Besides, each 0.05-mile section with an IRI value greater than 150 in/mi shall be corrected until the IRI value is at least 150 in/mi. Bushhammering or any other method involving impact will not be allowed. The Contractor will not be allowed to make corrective actions to increase his/her percentage of pay when the IRI is 150 in/mi or less.

e. Pay Adjustments. Pay adjustments for bridge floors will be based upon the smoothness of each 0.05 mile, unless corrective action was required. When the IRI for the 0.05 mile is between 105 and 125 in/mi, the payment will be made at 100% of the contract unit price for that section. When the IRI for of a 0.05 mile section exceeds 125 in/mi but does not exceed 150 in/mi, the contract unit price for that section will be reduced according to the Price Adjustment Schedule. On the other hand, when the IRI a 0.05 mile section is less than 104 in/mi, the contract unit price for that section will be increased, as is also shown in the following Price Adjustment Schedule

Price Adjustment Schedule

IRI (in/mi)	Percentage of unit bid price
< 80 in/mi	108
81-85	106
86-95	104
96-104	102
105-125	100
126-135	98
136-145	96
146-149	94
>150	Correction is required

Appendix L – Pennsylvania DOT Specification: Measuring Pavement Profile using a Lightweight Profiler

ROADWAY MANAGEMENT DIVISION

Method of Test for

MEASURING PAVEMENT PROFILE USING A LIGHT WEIGHT PROFILER

1. Scope
   1.1 This test method covers the measurement of pavement profile and roughness using a Light Weight Profiler (LWP) by driving the profiler longitudinally over the pavement.
   1.2 This test method covers the determination of the pavement ride quality from the longitudinal profile, as the pavement Profile Index (PI) for acceptance and payment, and also as the International Roughness Index (IRI). The test method also describes the procedure for the location of individual high points.

2. Referenced Documents
   2.1 ASTM Adjunct
   E950-94 Test Method for Measuring Pavement Roughness Using a Profiler
   2.2 NCHRP Report 228
   2.3 Light Weight Profiling System Calibration Verification and Operator Certification Program Manual

3. Terminology - Description of terms specific to this PTM:
   3.1 Must Grind Area – A 10 mm (0.4 in.) deviation of the pavement surface record from a chord representing 7.5 m (25 ft) on the longitudinal scale. The chord may represent less than 7.5 m (25 ft.) if it is from the lows on each side of the high. A deviation greater than 10 mm (0.4 in.) over the 7.5 m (25 ft.) is considered high point or low point requiring correction (Figure 1).

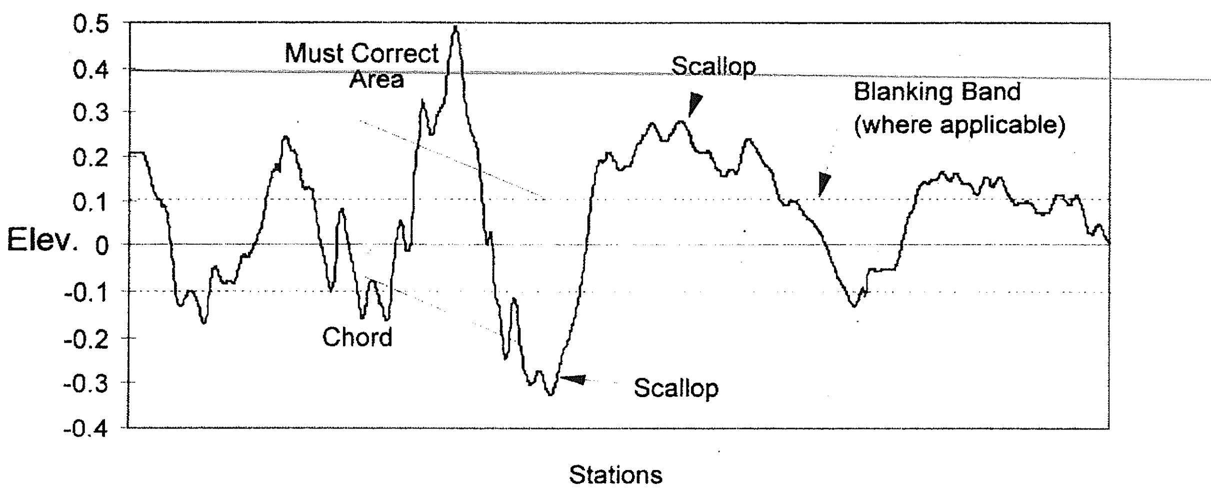


FIGURE 1. EXAMPLE PROFILE TRACE

3.2 Scallops – excursions of the surface record above and below the mathematically established baseline or band representing the digitized profile's central tendency (Figure 1).

3.3 Blanking Band – a band of uniform height with its longitudinal center positioned optimally between the highs and lows of the pavement surface profile (Figure 1). Width of band is specified, typically 0.0 mm (0.0 in.). Only scallops that extend above or below the specified band are measured.

3.4 Excluded Area - an area that is not included in the measurement of profile used to determine lot payment.

3.5 Profile Index (PI) – sum of the scallop divided by the longitudinal distance over which the profile is measured. Analogous to the results of a California type profilograph.

3.6 International Roughness Index (IRI) - a scale for roughness based on the response of a generic motor vehicle to roughness of the road surface. IRI was developed as a reference measure by The World Bank, and is based on a quarter-car simulation as described in NCHRP Report 228. IRI is determined by obtaining a suitably accurate measurement of the profile of the road, processing it through an algorithm that simulates the way a reference vehicle would respond to the roughness inputs, and accumulating the suspension travel.

4. Apparatus

4.1 The Light Weight Profiling System shall be an all-terrain or golf-cart type vehicle equipped with various hardware and software that together shall allow the measurement and recording of the longitudinal profile of a traveled wheel track and the reference distance traveled along the traveled wheel track. The device shall meet the requirements of the "Generic Specification for Light Weight Profiling System," Appendix A. (Disregard Items 11 and 12 of Appendix A, which refer to equipment supplier obligations, and note that Item 13 is optional.) The device must be verified, and the operator must be certified, by the Bureau of Maintenance and Operations, Roadway Management Division, on an annual basis. Additionally, re-verification/re-certification of devices or operators may be required by Department personnel, due to repairs, replacements, and/or upgrades to the device's hardware or software, or questionable results and/or practices on a construction or maintenance project. Verification/certification will be done in accordance with the Light Weight Profiling System Calibration Verification and Operator Certification Program Manual.

4.2 Software

4.2.1 The test software shall activate the testing using the timing and control parameters stored by the test control setup software. The software shall monitor the signals to verify that the testing is being performed properly and indicate detectable errors.

4.2.2 The test software shall receive, display, and store raw data received from the vehicle mounted transducers, and corresponding distance and test speed.

4.2.3 The system shall be capable of the requirements of Appendix A.

5. Sampling
Pavement profiles shall be taken in the wheelpaths of each lane. The first profile shall be approximately 1m (3 ft.) from and parallel to the outside edge of pavement, and the second profile shall be approximately 1.75m (5.75 ft.) from the first profile, or as directed by the Project Engineer. Measure profiles to the limits of the pavement areas, as specified. As per Specifications, Publication 408, sampling areas shall be designated as lots, and excluded areas shall be defined and measured separately. (Measure profiles of the excluded areas to their limits.)

6. Calibration
   6.1 The operational system software shall allow the operator to perform a distance sensor calibration and use the calculated Distance Calibration Factor (DCF) to perform the operational distance measurements. The calibration software shall also allow the operator to save the calculated DCF or change it to other than the calculated value. The operator shall only need to enter the distance traveled in feet, kilometers, or miles and not make any calculations to determine the DCF. 5 ft. per mi. accuracy is required.
   6.2 The calibration software shall also allow the operator to perform a profile system calibration. The values determined in calibration shall be stored and recorded as above for use in calculation.

7. Procedure
   7.1 Startup and initialization.
   7.1.1 Clear the intended LWP path of all loose material and foreign objects.
   7.1.2 Perform all necessary start up procedures.
   7.1.3 Verify that distance measurement, sensors, and accelerometers are properly calibrated. Perform all necessary calibration procedures, as specified in section 6, and as per equipment manufacturer procedures. Save all values.
   7.1.4 Check that all sensor positions are displaying correctly, and verify that sensor collection rates are properly set.
   7.1.5 Enter the location identification information (all data collected must have this information printed on all outputs), and define the direction of traffic for the pavement to be tested.
   7.2 Data collection.
   7.2.1 Position the LWP to a point where testing speed can be reached before testing begins. When possible, it is recommended to collect at least 100 ft. of data before the area to be tested to eliminate all error through filtering in the report program which processes the data. When this is not possible, provisions are necessary in the report program to eliminate some of the beginning and or ending test data to minimize the error.
   7.2.2 Verify that all software and hardware is ready to collect data. Start the data collection system.
   7.2.3 Remain stationary and wait for the system filters to stabilize (approximately one minute).

7.2.4 Start moving and initiate testing when the LWP reaches testing speed.
7.2.5 If targeting is used, allow target to reset system at test start and finish.
7.2.6 Continue testing at a consistent speed until the test end point is passed.
7.2.7 Terminate test after the test end point is passed, or allow targeting to terminate test.
7.2.8 End data collection and save the file. It is recommended to save all data, and then delete unwanted data later, rather than abort the file save mode.
7.2.9 If applicable, mark where the total file may be broken into smaller files for analysis.
7.2.10 Upon completion of a sampling path, make ending notations and review the test for reasonableness. Repeat the procedure, driving the LWP in the same direction for successive sampling paths for a given section of pavement. Test each sampling path only once. Additional profiles may be taken to define the limits of an out-of-tolerance surface variation.
7.2.11 Measure PI and IRI for excluded areas separately.

8. Report

As a minimum, the following information shall be printed for the interpreted output for each wheelpath:

(1) Date and time of day
(2) Operator and equipment identification
(3) Weather conditions: temperature, cloud cover, and wind
(4) Surface description: type of pavement and condition
(5) Location and description of section: Job ID, lot, lane, wheelpath, beginning and ending stationing, and direction measured
(6) Must grind areas to the nearest 1mm (0.05 in.)
(7) Data filter settings
(8) Lot Length
(9) Scallop (Filter)
NOTE: Filter setting = 22.5 / ((DCF value / 65,536) x 12)
(10) Minimum Height 0.75 mm (0.030 in.)
(11) Minimum Width (300:1) 2.00 mm (0.08 in.)
(12) Resolution 0.25 mm (0.01 in.)
(13) Blanking Band 0.00 mm (0.00 in.), or as specified
NOTE: Blanking Band applicable to PI only.
(14) Defect Template Height 10.00 mm (0.40 in.)
(15) Lot PI value: the average of the two wheelpaths for each lot will be the PI for the lot
(16) Lot IRI value: the average of the two wheelpaths for each lot will be the IRI for the lot
(17) PI and IRI values for excluded areas

End of PTM 428

GENERIC SPECIFICATION FOR LIGHT WEIGHT PROFILING SYSTEM

The purpose of this specification is to define the requirements for a Light Weight Profiling (LWP) System that can be used to collect roadway surface data for determining the roughness and profile of roads. The following items are required:

1. The computer based system, with its profile sensing system described shall be capable of the following:

    (1) interfacing with the operator
    (2) controlling the tests
    (3) measuring the necessary resultant test signal data
    (4) recording the resultant test data on IBM-PC compatible floppy diskettes
    (5) calculating and storing profile, roughness and distance values
    (6) displaying the stored data
    (7) printing the stored data upon operator request

2. The lightweight profiler operational system shall be equipped with various hardware and software that together shall allow the measurement and recording of the longitudinal profile of a traveled wheel track and the reference distance traveled along the traveled wheel track. The Longitudinal profile shall be measured using a concept where three transducers are used. These transducers include:

    (1) a height sensor which measures the distance between a vehicle reference point and the pavement while the vehicle is driven over the roadway.
    (2) an accelerometer which measures the vertical acceleration of the vehicle as it bounces in response to the road profile.
    (3) a distance sensor which provides a reference measurement of the vehicle as it traverses the pavement.

    The data shall be saved and recorded so that road profiles obtained with this system shall be independent of the measuring speed and the type of vehicle used. After the post processing software is utilized the measured profiles must show variations in elevation and slope as they affect roughness. In addition, profile plots must be capable of being displayed on a computer screen or on hard copy after post processing. The system shall be capable of obtaining and storing profile measurement data at selected longitudinal distance intervals down to a minimum of 1 reading per approximately 1 inch.

3. The roughness value shall be calculated using the standardized International Roughness Index (IRI), or PI. In addition to the normal IRI unit value the system shall also provide an "in/mi" statistic. The IRI was developed as a reference measure by The World Bank, and is based on a quarter-car simulation as described in NCHRP Report 228. This value shall conform to the Class 1 requirements of ASTM E950-94. IRI measures obtained from this system shall match those obtained from other valid profilometers, and also IRI measures obtained using rod and level survey equipment. A plot of roughness using any base length for averaging shall also be producible. The above roughness results shall be displayable on the system screen, printed on a printer or written into a disk file for processing.

4. The profile system hardware and software for collecting and processing the data obtained in real time in conjunction with the post processing software must have as a minimum the following capabilities:

   (1) profile computation
   (2) RN/PI computation
   (3) IRI computation
   (4) high-pass filtering
   (5) low-pass filtering (smoothing)
   (6) height sensor error checking

5. The system shall be capable of calculating, displaying, and storing the average roughness value obtained from the stored data. Additionally, the system shall be capable of putting the accumulated roughness test results through mathematical equations and printing results when enabled by the operator. These options shall be done in real time or in post processing. The system shall be capable of performing all required post processing operations. The post processing software shall be capable of running on a IBM compatible PC with a SVGA monitor where graphics are used.

6. The operational system through the Distance/Data Acquisition Subsystem (DAS) shall provide all interfaces to collect data to derive distance, speed, and profile from the transducers mounted on the vehicle; shall activate the tests; derive distance and location information from the transmission mounted distance and shall process operator inputs from the keyboard and Event Keyboard signaling that the test vehicle has encountered a significant feature; and shall pass information on the feature and it's location to the processing unit for display and logging.

7. An optical encoder shall be mounted on the vehicle to produce a pulse for units of distance traveled by the vehicle on the roadway. The DAS shall accept these pulses and in combination with the DAS software shall determine distance traveled and vehicle speed.

8. The reference height of the vehicle above the pavement shall be obtained through a laser or infrared module as required. The sensor shall be totally enclosed in a case that may be sealed during bad weather or when not in use. The sensor shall be formed in a manner so that it may be mounted on a vehicle approximately 1 foot above the pavement surface. The laser or infrared module should be equivalent to a Selcom sensor, which has a resolution of .001 inches. The sensor shall provide continuous coverage of the roadway. The sensor module shall send an infrared beam to the pavement and sample the height value at a rate of 16,000 times per second. The samples shall be averaged and stored referenced to time and/or distance so that it may be processed into transverse profile data or aligned with the accelerometer data to provide longitudinal profile.

9. The displacement of the vehicle in the vertical direction used to calculate position should be sensed using an accelerometer. The DAS shall provide hardware and software to amplify and filter/integrate the signal as required to obtain the data required for storage and for further post processing into the required data.

10. Upon delivery of the system, the equipment supplier shall provide a complete description of the format of all files generated by the software, such that data files can be prepared on disks in a format necessary for the software to read and process all of the items defined in Item 4.

11. Upon delivery of the system, the equipment supplier shall also provide:

    (1) One copy of operating procedures for all operational software.
    (2) One copy of schematics, block diagrams and wiring diagrams covering electronic circuitry of the installed system.
    (3) One complete parts lists detailing the components of all equipment used.
    (4) A three day training session on the use of the new equipment, and a one day training session on data reduction.

12. The equipment supplier shall warrant all components of the operational system for a period of not less than one (1) year from date of acceptance to be free from defects in material and workmanship.

The following item is optional:

13. The vehicle will be equipped with infrared sensors to allow the operational system to perform system functions (start test, end test, reset DMI value, etc.) without operator intervention when using roadside targets.

Appendix M – Texas DOT Specification: Operation of Pavement Inertial Profilers and Evaluation of Pavement Profiles

Texas Department of Transportation
Materials and Test Section of the Construction Division

OPERATION OF PAVEMENT INERTIAL PROFILERS AND EVALUATION OF PAVEMENT PROFILES

Scope

This test method describes the procedure for the operation and the verification of calibration of an inertial profiler. It also provides evaluation procedures for the profiles that are generated. It provides a methodology for resolution of disputes arising from suspect profiler output.

Apparatus

An inertial profiling system consists of a minimum of the following components.

- A housing vehicle capable of traveling at speeds of a minimum of 12 mph while collecting pavement profile data.
- A distance measuring subsystem that is accurate to within 2 feet per 528 feet of distance traveled.
- An inertial referencing subsystem capable of measuring the movement of the housing vehicle as it traverses the pavement under test.
- A non-contact height measurement subsystem capable of measuring the height from the mounted sensor face to the surface of the pavement under test.
- The inertial profiler will have hardware and software capable of producing and storing inertial profiles by combining the data from the inertial referencing subsystem, the distance subsystem, and height measurement subsystem.
- The inertial profiler will have the capability of measuring and storing profile elevations at 6-inch intervals or less. It will be capable of outputting these elevations in the format prescribed in Attachment A.
- The inertial profiler will have the capability of summarizing (computing) the profile elevation data into summary roughness statistics over a section length equal to 0.1-mile.
- The summary roughness statistic prescribed is the International Roughness Index (IRI) for each longitudinal wheel path profiled.
- The inertial profiler will be of such design to allow field calibration and verification of calibration for the distance measurement (horizontal) subsystem and the height measurement (vertical) subsystem.
- The inertial profiler will be certified for use in Texas. The certification procedure is documented in Attachment D.

For consistent pavement profile determination, air pressure on the wheels of the housing vehicle shall be maintained in accordance with manufacturer's specification. The housing vehicle and all system components will be in good repair and proven to be within the manufacturer's specifications. The operator of the inertial profiler shall have all tools and components necessary to adjust and operate the inertial profiler according to the manufacturer's instructions.

Repair and Adjustment of Inertial Profilers

Major component repairs or replacement to an inertial profiler that would cause the re-certification of the equipment include but is not limited to the following. Repair or replacement of:

- The accelerometer and its associated hardware.
- The non-contact height sensor and its associated hardware.
- Any printed circuit board necessary for the collection of raw sensor data or the processing of the inertial profiles and IRI.

The operator of the inertial profiler will be allowed to make minor adjustments to the equipment without having to complete the re-certification process as long as the adjustments allow the equipment to fulfill the following verification of calibration process. Minor adjustments to the system include but are not limited to the following:

- Inspection, re-soldering, or replacement of connectors.
- Cleaning of components, normal adjustments to voltage levels as required by the manufacturer.
- Setting of software parameters and/or scale factors as required by the manufacturer.

Verification of Calibration

1. Standards

   a. Horizontal

   The horizontal or longitudinal calibration standard shall be a straight roadway test section of 528 feet in length. This length shall be measured accurately to within 1 foot using a steel measurement tape.

   b. Vertical

   The vertical measurement standard shall be flat plates of known thickness. These plates shall be marked with the known thickness. As a minimum, a quarter-inch base plate, a quarter-inch measurement plate, a half-inch measurement plate, and a one-inch measurement plate shall be tested. The thickness of each measurement plate shall be certified accurate to within 0.001 inch.

2. Procedure

   a. Frequency of Verification of Calibration

The horizontal and vertical verification of calibration of the inertial profiler will be performed prior to use on each paving project, at any time the profiler does not meet the tolerances established under the control section described below, and at such times as the Engineer determines verification is necessary. The tire air pressure on the wheels of the housing vehicle shall be checked at least daily and maintained in accordance with the manufacturer's recommendations. A log will be maintained with the inertial profiler to provide a verification of calibration history.

b. Horizontal Verification of Calibration

The horizontal (longitudinal) verification of calibration shall be performed by navigating the inertial profiler over a measured test section of 528 feet in length. The inertial profiler's distance measuring subsystem must measure the length of the test section to within 2 feet of its actual length. Adjustments to the inertial profiler's distance measurement subsystem will be accomplished according to the manufacturer's guidelines. Failure to meet the specified tolerance will require re-calibration by the Contractor and re-verification as described above.

c. Vertical Verification of Calibration

The vertical verification of calibration shall be performed on a flat and level area using the flat plates of known thicknesses. The base plate is placed under the inertial profile's non-contact height sensor. The inertial profiler's height measurement subsystem shall take a height measurement. This measurement will be used as the reference height for subsequent measurements. Place the quarter-inch plate on top of the reference plate below the non-contact sensor. The inertial profiler's height measurement subsystem shall measure this displacement to within 0.01 inch of the quarter-inch block's thickness. Remove the quarter-inch block and replace it with the half-inch block. The inertial profiler's height measurement subsystem shall measure this displacement to within 0.01 inch of the half-inch block's thickness. Remove the half-inch block and replace it with the one-inch block. The inertial profiler's height measurement subsystem shall measure this displacement to within 0.01 inch of the one-inch block's thickness. Remove the one-inch block and verify that the inertial profiler's height measurement system returns to the original reference plate's displacement to within 0.01 inch. Failure to meet the specified tolerance will require re-calibration. If the re-calibration requires major repair as noted above, then the profiler shall be re-certified at the TTI Annex. Otherwise, it shall be re-verified as indicated above.

d. Control Section

To ensure that the equipment selected for measuring smoothness is maintained in proper operating condition during the course of the paving project, the Contractor shall establish a 0.1-mile control section as approved by the Engineer. The Contractor shall use this section to establish and maintain a control chart for his or her equipment as specified in Attachment C of this test method. When a profilograph is being used, the PI values from this control section shall be converted into IRI values using the following equation:

$$IRI = \frac{4.445 \times PI}{1 + (0.02073 \times PI)}$$

The Contractor shall propel the profiler over the 0.1-mile control section for 10 consecutive test runs. The spacing between the two wheel paths of the control section will be 69 inches. An IRI will be calculated for each of the test runs. The control section must have an average IRI of 95.0 in/mile or less and the standard deviation of the repeat runs must be 3 in/mile or less. Prior to evaluating the surface smoothness of the day's production, the contractor shall run his or her equipment on the control section. The contractor shall use the average IRI from this run to check the equipment as explained in Attachment C. The equipment must satisfy the control limits specified in Attachment C before it can be used for quality assurance of the day's production. Failure to meet the specified control limits will require re-calibration of the profiler by the Contractor. The profiler shall then be re-tested on the control section to determine compliance. If minor adjustments, as noted above, are required, then the profiler shall be re-tested on the control section to determine compliance. If major repairs are performed, as described above, the inertial profiler shall be required to obtain a re-certification at the TTI Annex. The profiler shall not be used for quality assurance testing until the contractor can show, to the satisfaction of the Engineer, that the equipment is within the acceptable limits of the control chart.

Test Procedure

Prior to measuring the pavement profile, the roadway path to be measured shall be clean of all debris and other loose material.

When measuring the pavement profile, the inertial profiler shall be operated at a constant speed of 12 mph or greater. Failure to maintain this minimum speed will cause the inertial referencing subsystem to "droop"; hence the pavement profile elevations will not be usable. Any pavement segment that has an average operational speed of less than 12-mph shall be re-measured.

A pre-section length of roadway is required to "settle" the inertial profiler's filters. This pre-section shall be at least 200 feet in length and located immediately before the section of pavement under test. The inertial profile measurements shall be taken on two longitudinal lines representing the wheel paths in each travel lane. These longitudinal lines shall be 69 inches apart. For pavement travel lanes wider than 12 feet, inertial profile measurements may be required near each longitudinal joint as well as the wheel paths. If the inertial profiler is capable of measuring profiles from two longitudinal wheel paths during a single pass, then the wheel path spacing shall be 69 inches.

Measurements will be collected in the direction of traffic. The measurements from each wheel path shall start and stop at the same longitudinal location.

Event markers may be placed in the elevation data during the measurement process, if the inertial profiler has this capability. These event markers should be used to indicate the location of roadway features such as reference markers, stationing, or bridge ends in the data file.

The profile elevation data shall be presented to the Engineer in an electronic form (on floppy disk) with a file format as described in Attachment A of this test method. The Engineer will use TxDOT software to calculate the IRI values and the associated pay factors.

A summary roughness statistic shall be computed for each 0.1-mile pavement segment. This roughness statistic is the International Roughness Index (IRI). The IRI from each longitudinal line profiled for a pavement travel lane shall be calculated and recorded. The payment schedule will be based on the average IRI calculated from both wheel paths in a travel lane.

Segment Less Than 0.1 Mile

Segment lengths less than 0.1 mile and greater than 50 feet will be calculated as illustrated in the following example:

•Suppose that the length of the short section is 0.075 miles;
•The measured IRI = 37 in/mile; and
•That the pay is $100 for a full 0.1-mile section with an IRI= 37 in/mile.

$$Pay\ adjustment \quad = \quad \$100 \times \frac{0.075}{0.100} = \$75$$

Resolution of Profile Disputes

At any time during the course of the paving operation, the Engineer may perform independent ride quality testing using a certified TxDOT inertial profiler. If the difference between the TxDOT IRI value over a 0.1 mile section is more than +/- 12.0 inches per mile from the IRI obtained using the Contractor's equipment over the same 0.1 mile section, then the Engineer and the Contractor shall attempt to resolve the differences. If the differences cannot be resolved, then the Engineer may request referee testing. All referee testing will be conducted by the Design Division and will be final.

If the Contractor is using an inertial profiler, TxDOT will use an independent and certified inertial profiler for the referee testing. Comparison tests shall be performed on the Contractor's previously established control section. Prior to testing, the control section shall be cleaned of debris and the wheel paths shall be marked. The Contractor shall make ten measurements of the profiles on the control section using his or her equipment. The Contractor shall provide all profile measurements to the Engineer in electronic data files with the format specified in Attachment A. Likewise, ten measurements will be made using the Design Division's referee profiler on the same wheel paths. All profile measurements will be made in the same direction.

The IRI will be calculated for each wheel path profile determined from a given run. A statistical analysis will be made in accordance with Attachment B. The statistical test will be made at a confidence level of 95 percent. The analysis of the data for this comparative testing will be made using TxDOT's computer program for referee testing developed for this test method. If the analysis shows a significant difference between the Contractor's profiler and the referee profiler, the Contractor's profiler will be reported as non-compliant and its certification will be revoked. The Design Division's referee profiler will then be used to establish pay adjustment factors for all sections in question. The Contractor shall be required to have the non-compliant profiler re-certified or otherwise obtain a profiler with a valid certification. While a replacement profiler is being obtained, the Contractor may request in writing that the project continue for a period of not more than five working days and be tested after a replacement profiler has been obtained. Any bonus or penalties accrued during the five day period shall be assessed upon proper measurement with a certified profiler. The Contractor will not be allowed to replace an inertial profiler with a profilograph.

If the statistical analysis shows the Contractor's inertial profiler to be within tolerance, then the TxDOT Regional profiler will be taken out of service until it has been re-certified. The Contractor's results will be used to establish pay factor adjustments.

If the Contractor is using a profilograph, the control section tests described above shall be used to determine if the Contractor's profilograph is defective. The Contractor shall replace or repair any defective profilograph. While a replacement profilograph is being obtained, the Contractor may request in writing that the project continue for a period of not more than five working days and be tested after a replacement profilograph has been obtained. The Contractor may replace a profilograph with a certified inertial profiler.

ATTACHMENT A. TEST DATA DESCRIPTION AND FORMAT

Referee Test Data

Profile data from each of the ten runs made on the designated wheel path of each test section shall be provided in an electronic file in ASCII or text format. Test data must be reported in mils and in an ASCII file. This will permit TxDOT to directly input profile data, collected with any lightweight inertial profiler, into its data reduction program for referee testing. The required format of the data file is illustrated in Figure 1 and explained as follows:

First Record: The first record will consist of the following items, each separated by a comma:

a. The first item is the identifier for the record. This shall be written as **HEAD3** in the data file as illustrated in Figure 1.
b. Date of profile measurement in *mmddyyyy* format where *mm* is the numeric designation for the month, *dd* is the day, and *yyyy* is the year.
c. District where profile measurements were made in ## format. Note that ## is the two digit numeric designation for the given District.
d. County number in ### format.
e. Highway name in $$####$ format where $ in represents a character descriptor.
f. Beginning reference marker of the measurement in ####$+##.### format.
g. Lane tested in $# format following PMIS convention.

Second Record: The second record will have the following variables, each separated by a comma:

a. The first item is the identifier for the record. This shall be written as **CMET3** in the data file as illustrated in Figure 1.
b. Model designation of the lightweight profiler used for testing.
c. The third, fourth, fifth, and sixth items in the record are reserved for the use of the profile manufacturer or the contractor. Note that if these items are blanks, the comma delimiting each item must still appear in the record as illustrated in Figure 1.
d. The seventh item in the record is the certification number for the given profiler that is issued by the testing agency upon passing the Lightweight Profiler Equipment Specification testing.
e. The last item in the record is the certification date in *mmddyyyy* format.

Third Record: The third record will have the following variables, with a space separating each variable:

a. Name of the Manufacturer of the lightweight profiler (alphanumeric).
b. The unit of length used to report profile. Under the current TxDOT practice, this shall be mil (0.001 inch) as shown in Figure 1.
c. The wheel path measured designated as L for left, R for right, or LR for dual wheel path profilers. Note that L and R are relative to the direction of traffic

on the lane surveyed. For dual wheel path profilers, the order in which the L and R appear shall correspond to the order in which the relative elevations at a given station are reported in the file. Thus, if the entry is LR, the left wheel path elevation is reported first, followed by the right wheel path elevation at a given station.

d. The reporting interval (distance between successive relative elevation measurements) in inches.

e. The units of the reporting interval item (d) above. Either i = inch or m = meters.

Fourth and Fifth Records: The fourth and fifth records are reserved for text comments and can have any desired format.

The first five records of the ASCII data file are thus header cards. Following the fifth header record, the relative measurements at each station are reported. For profilers that measure only one wheel path in a given run, there shall be a column of numbers after the fifth header record consisting of the relative elevations measured at different locations or stations along the lane surveyed. Profile measurements will be made in the direction of traffic. There shall be as many records following the fifth header card, as there are stations where elevation measurements have been collected.

For profilers capable of measuring two wheel paths in a travel lane at the same time with one pass, the profile data will consist of two columns of elevations. One set of measurements taken using the sensors on left side of the profiler, and the second set using the sensors on the right side. Profile measurements will be made in the direction of traffic. For these profilers, the spacing between wheel path sensors shall be set at 69 inches to be consistent with TxDOT practice. Thus, for each station where elevation measurements have been taken, there will be a record in the data file which will report the elevations for each wheel path tested, with a space separating the two wheel path elevation readings at the same station. The order in which wheel path measurements are reported must be consistent with the wheel path descriptor written in the third header card item (c) of the ASCII data file.

During the referee testing, the same wheel path(s) is measured for all ten runs on a given test section. There will be twice more data collected and analyzed when single wheel path inertial profilers are tested. To facilitate the analysis of the data, the files from the tests described herein shall be named according to the following convention:

Filename: For Contractor's profilers, the filename will begin with **CONT** followed by an alphabetic character **A** through **Z**. For TxDOT profilers the filename will begin with **TDOT** followed by an alphabetic character **A** through **Z**. If multiple Contractor profilers are to be tested, the first profiler to be tested will be designated by the character **A**. The next profiler to be tested will be designated with the character **B** and so on. This same convention will be used for testing multiple TxDOT profilers.

Extension: The first character in the extension of each data file will designate the wheel path(s) that are included in the file. The character **L** will be used to indicate the left wheel path. The character **R** will be used to indicate the right wheel path. The character **B** will be used to indicate that the file contains both (two) wheel paths. Numeric characters will follow the wheel path designation in the extension. The numeric character will be used to designate the run number associated with a particular file. For profiler's measuring a single wheel path, the first run will be numbered **01**; the second run will be numbered **02** and so on to the **20th** run. For profiler's measuring two wheel paths in one pass, the first run will be numbered **01**; the second run will be numbered **02** and so on to the number **10**.

Example Filename: CONTA.L01
This filename indicates that the data is from the Contractor's profiler designated A, the left wheel path elevations are in the file, and the data is from run #1.

```
HEAD3, 06241999, 17, 21, SH0047, 0413 +00.200, R1
CMET3,Profiler Model,,,,,Certification number, Certification date
Manufacturer  mil  LR  5.4882 I
COMMENT
COMMENT
-797  -869
-796  -834
-781  -824
-752  -821
-746  -824
-752  -811
-738  -790
-702  -756
-696  -738
-704  -727
-706  -730
-669  -708
-649  -705
-644  -702
-645  -668
-610  -674
-568  -635
-560  -627
-574  -620
-568  -591
-534  -588
-501  -571
-480  -549
-463  -547
-457  -493
-415  -486
-396  -454
-398  -425
-370  -398
-351  -369
-335  -353
-325  -328
-308  -305
-286  -297
-257  -274
-253  -250
-228  -238
-206  -188
-187  -202
```

Figure 1. Required Format of Profile Data File.

ATTACHMENT B. STATISTICAL COMPARISON OF COMPUTED SECTION IRIs

A. The mean of the ten section IRIs determined from the profiles taken with each profiler is computed by getting the sum of the section IRIs and dividing the result by ten.

B. The standard deviation of the ten section IRIs from a given profiler is computed from the formula:

$$s = \sqrt{\frac{n\sum_{i=1}^{n} x_i^{\,2} - \left(\sum_{i=1}^{n} x_i\right)^2}{n(n-1)}}$$

(**B1**)

where,

s	=	standard deviation of the section IRIs from a given profiler
n	=	number of observations which is 10
x_i	=	section IRI computed from the i[th] run of a given profiler

C. The following quantity, known as the standard error of the difference, is computed:

$$\sigma_{1-2} = \sqrt{\frac{s_1^{\,2} + s_2^{\,2}}{(n-1)}}$$

(**B**2)

where,

σ_{1-2}	=	standard error of the difference
s_1	=	standard deviation of the section IRIs from the contractor's profiler
s_2	=	standard deviation of the section IRIs from TxDOT's profiler
n	=	number of observations which is 10

D. The *t*-statistic is computed from the means of the section IRIs computed in step A, and the standard error of the difference in step C, as follows:

$$t = \frac{IRI_{avg1} - IRI_{avg2}}{\sigma_{1-2}}$$

(**B**3)

where,

IRI_{avg1} = mean of the section IRIs from the contractor's profiler
IRI_{avg2} = mean of the section IRIs from TxDOT's profiler
σ_{1-2}= standard error of the difference computed in step C

E. To test if the mean of the section IRIs from the contractor's profiler is significantly different from the corresponding mean determined from TxDOT's profiler, take the absolute value of the t-statistic in step D. If this absolute value is greater than 2.101, the test results show a significant difference between the contractor's and TxDOT's profiler at a confidence level of 95 percent.

ATTACHMENT C. ESTABLISHING AND MAINTAINING A CONTROL CHART

I. PURPOSE AND SCOPE

To ensure that profiling equipment is maintained in good operating condition during the course of a project, the contractor shall establish a 0.1-mile control section for evaluating his or her equipment as explained in this attachment. This evaluation will require the contractor and Engineer to establish and maintain a control chart to monitor the performance of the profiler or profilograph from measurements taken on the control section. A statistically based method is provided for detecting out-of-tolerance conditions and establishing the need for equipment calibration or servicing. The following operational issues are covered: 1) establishing a control section; 2) scope and frequency of testing; 3) control chart construction; and 4) control chart application. In practice, the procedure to establish and maintain a control chart is simply implemented using a computer program.

II. ESTABLISHING THE CONTROL SECTION

The contractor shall establish a 0.1-mile control section as approved by the Engineer. For this purpose, it is strongly recommended that the section be located where it will receive little to no truck traffic to minimize changes in the surface profile during the course of the project on which it will be used. If it is determined, at any time during construction, that the surface profile of the section has changed, another control section will have to be established as well as a new control chart.

The contractor shall identify alternative sites for the control section to the Engineer. Since the control section is required to have an average IRI of 95 in/mile or less, the contractor may have to collect profile data to identify sites that meet this requirement. In addition, when an inertial profiler is used, a pre-section is required to settle the filters of the instrument as specified in this test method. The pre-section must be at least 200 feet long and leads into the control section. A lead-out section is also necessary to safely bring the inertial profiler to a stop after the measurement on the control section.

After a site is selected, the contractor shall delineate two 528-ft longitudinal lines on the pavement surface corresponding to the wheel paths of the control section. The contractor shall layout the wheel paths by tape to achieve an accurate measurement of the stipulated 528-ft length and provide a reference for the horizontal calibrations that the contractor is required to perform according to this test method. In addition, the contractor shall mark the starting and ending locations of the control section on the pavement.

Each wheel path may be delineated by marking the pavement surface at regular intervals along its length with spray paint or other suitable markers. The distance between the wheel paths should be the same as the distance between the lasers of TxDOT’s inertial profiler (currently set at 69 inches). The Engineer shall provide the current wheel path settings to the contractor. Delineating the wheel paths will serve to guide the operator and minimize the variability associated with wheel path tracking during testing. For the purpose of monitoring profiling equipment, it is necessary that data be consistently taken on the same wheel paths. In addition, delineating the wheel paths will help the contractor achieve the repeatability that is required for the initial profile measurements specified in Item III of this attachment. The test method stipulates a 3 in/mile or less standard deviation in the IRIs determined from the initial runs.

III. SCOPE AND FREQUENCY OF TESTING

Prior to profile measurements on the control section, the contractor shall perform vertical and horizontal calibrations according to this test method and **shall** follow procedures specified by the equipment manufacturer. After the control section is established, the contractor shall make 10 repeat runs on each wheel path. The data from these runs will be used to verify the average IRI of the control section and to initialize the control chart as explained in Item IV of this attachment.

For each run, the average of the left and right wheel path IRIs is determined. This average is referred to herein as the section IRI. Thus, 10 section IRIs shall be determined from the initial set of runs made. For the control section to be accepted, the average of the section IRIs shall be no greater than 95 in/mile. In addition, the standard deviation of the IRIs must be no more than 3 in/mile for the purpose of establishing the control chart.

Once the chart is initialized, the contractor shall make one run on each wheel path of the control section prior to using the equipment for evaluating the surface smoothness on the day's production. Data from the daily runs are used to track the operational worthiness of the contractor's profiling equipment using a statistical process control tool known as cumulative sum (CUSUM) charting. The procedure for constructing this chart is presented in the following.

IV. ESTABLISHING THE CONTROL CHART

The CUSUM charting procedure presented herein uses the profile measurements specified in Item III for calibrating the chart and maintaining control. The approach adopted is described by Hawkins and Olwell (1998) as a "self-starting" CUSUM. The interested reader is referred to Hawkins and Olwell (1998) for a detailed explanation of CUSUM charting. In practice, the control chart is simply constructed and updated using a computer program written for this purpose. An example chart is given in Item VI of this attachment. For the purpose of documentation, the steps in constructing the CUSUM chart are presented in the following.

A. Determine the IRI from the profile measurement taken on each wheel path for a given run. If the contractor is using the profilograph, the IRI is computed from the null blanking band Profile Index (PI_0) using the equation:

$$IRI = \frac{4.445 \times PI_0}{1 + (0.02073 \times PI_0)} \tag{1}$$

where PI_0 and IRI are in in/mile. If the contractor is using an inertial profiler, the IRI is computed from the corresponding measured profile using data processing software incorporated with the profiler. The average of the left and right wheel path IRIs is determined and used for control charting.

B. For each run, calculate the running mean and variance of section IRIs using the following equations:

$$\overline{IRI}_n = \overline{IRI}_{n-1} + \frac{IRI_n - \overline{IRI}_{n-1}}{n} \tag{2}$$

$$Var_n = Var_{n-1} + \frac{(n-1)(IRI_n - \overline{IRI}_{n-1})^2}{n} \tag{3}$$

where,

IRI_n	=	section IRI for run n
$\overline{IRI}_n$	=	average of section IRIs from runs 1 to n (a running mean)
$\overline{IRI}_{n-1}$	=	running mean corresponding to the previous run
Var_n	=	variance of the section IRIs from runs 1 to n (a running variance)
Var_{n-1}	=	running variance corresponding to the previous run

Compute the standard deviation SD_n corresponding to run n using the equation:

$$SD_n = \sqrt{\frac{Var_n}{(n-1)}} \tag{4}$$

Note that the running mean corresponding to run 1 is the same as the section IRI for that run. Also, the running variance at run 1 is zero and the corresponding standard deviation is not computed [Eq. (4) is used for $n > 1$].

C. For $n > 2$, standardize the section IRI for the given run using the running mean and standard deviation of the preceding observations in the following equation:

$$T_n = \frac{IRI_n - \overline{IRI}_{n-1}}{SD_{n-1}} \tag{5}$$

where T_n is the standardized section IRI for run n and the other terms are as defined previously. Multiply T_n by the factor a_n which is determined from the equation:

$$a_n = \sqrt{\frac{n-1}{n}} \tag{6}$$

D. For $n > 2$, transform T_n into an independent normal random variable U_n having a mean of zero and variance of one. This is done by evaluating the cumulative t distribution function at a_nT_n with $(n-2)$ degrees of freedom and getting the inverse normal function of the resulting quantity.

E. For each run n, evaluate the following cumulative sums to detect positive or negative mean shifts in the section IRIs determined from the profile measurements on the control section:

$$S^{+}_{n} = \max(0, S^{+}_{n-1} + U_n - k) \quad (7)$$
$$S^{-}_{n} = \min(0, S^{-}_{n-1} + U_n + k) \quad (8)$$

where $S^{+}_{0} = S^{-}_{0} = 0$ and k is half of the magnitude of the shift (expressed in standard deviation units) that one wishes to detect. For this test method, a mean shift of two standard deviations is used so that $k = 1$. The cumulative sums are compared to upper and lower control limits denoted by h^{+} and h^{-}, respectively, to detect an "out-of-tolerance" condition. For this test method, $h^{+} = h^{-} = 1.96$.

V. APPLICATION OF THE CUSUM CHART

In practice, the Contractor shall use a TxDOT computer program to evaluate the cumulative sums from the profile data following the procedure described in the previous section. The cumulative sums S^{+}_{n} and S^{-}_{n} may be tabulated and/or plotted in a control chart where the y axis is the cumulative sum and the x axis is the run number. On the same chart, the upper and lower control limits may also be plotted as horizontal lines corresponding to $y = \pm 1.96$. Whenever S^{+}_{n} exceeds 1.96 or S^{-}_{n} becomes less than –1.96, an "out-of-tolerance" condition is detected which requires the contractor to check his or her process. When this event occurs, the following guidelines are offered for the contractor's consideration:

A. Have the operator check the instrument settings used on the last run. For a profilograph, the settings are printed on the output from the previous run. For an inertial profiler, verify the instrument settings according to the manufacturer's operating instructions. Make a repeat run. If a different result is obtained, recalculate the cumulative sums and compare against the control limits. If the repeat run passes, the Contractor uses its result to update the CUSUM chart and makes a note of this in his or her log book.
B. If similar results are obtained from the repeat run, review the calibrations that were conducted on the instrument. Repeat the calibrations as warranted and make another run.
C. If the instrument still does not pass after recalibration, the Contractor should contact the equipment manufacturer to have it checked and serviced. If the Contractor suspects that the surface profile of the control section has changed, he or she should discuss this with the Engineer. In this case, the Contractor may bring in another inertial profiler or profilograph to compare with the existing unit. If the alternative profiler or profilograph produces an IRI that satisfies the control limits, the Contractor's existing equipment should be serviced. Otherwise, if the alternative device fails, a new control section should be established.

VI. EXAMPLE CUSUM CHART

Table C1 shows how the calculations outlined in Item IV may be tabulated to keep a running record of the cumulative sums. The calculations are performed using a TxDOT computer program written for this test method. The first 10 IRI values in column 2 of the table are from the first set of runs made to initialize the CUSUM control chart. The IRI value shown for a given run is the average of the corresponding left and right wheel path IRIs and is expressed in inches/mile. The other columns in the table are explained as follows:

A. Column 3 shows the running means of the IRIs computed using Eq. (2).
B. Column 4 shows the running variance of the IRIs which are computed for each run using Eq. (3).
C. Column 5 gives the running standard deviation from Eq. (4).
D. Column 6 shows the standardized section IRIs (T_n) from Eq. (5).
E. Column 7 shows the product of a_nT_n where a_n is computed from Eq. (6).
F. Column 8 gives the value of the cumulative t distribution function evaluated at a_nT_n with $(n - 2)$ degrees of freedom.
G. Column 9 gives the inverse normal function evaluated at the cumulative t distribution function value from column 8.
H. Column 10 shows the cumulative sums computed from Eq. (7) for detecting positive mean shifts.
I. Column 11 shows the cumulative sums computed from Eq. (8) for detecting negative mean shifts.

Note that an "out-of-control" condition is detected at run 23 where S^+_n exceeds the upper control limit of 1.96. In this event, the contractor should check his or her process as explained in Item V to determine the reason for the "out-of-control" signal. When the cause has been identified and corrected, the cumulative sums should be restarted at the last occurrence of $S^+_n = S^-_n = 0$ (run 19 in Table C1). The cumulative sums in Table C1 are plotted in Figure C1 along with the upper and lower control limits of ±1.96.

VII. REFERENCE

Hawkins, D. M. and D. H. Olwell. *Cumulative Sum Charts and Charting for Quality Improvement*. Springer-Verlag Inc., New York, 1998.

Table C1. Example CUSUM Chart Calculations.

Run	IRI_n	$\overline{IRI}_n$	Var_n	SD_n	T_n	a_nT_n	Cumulative t-dist. function value	U_n	S^+_n	S^-_n
1	43.10	43.10	0						0.00	0.00
2	40.17	41.63	4	2.07					0.00	0.00
3	44.73	42.67	11	2.31	1.49	1.22	0.7815	0.78	0.00	0.00
4	47.83	43.96	31	3.20	2.23	1.93	0.9035	1.30	0.30	0.00
5	47.60	44.68	41	3.21	1.14	1.02	0.8080	0.87	0.17	0.00
6	49.20	45.44	58	3.41	1.41	1.28	0.8656	1.11	0.28	0.00
7	37.45	44.30	113	4.34	-2.34	-2.17	0.0413	-1.74	0.00	-0.74
8	43.30	44.17	114	4.03	-0.23	-0.22	0.4183	-0.21	0.00	0.00
9	47.29	44.52	122	3.91	0.77	0.73	0.7549	0.69	0.00	0.00
10	40.74	44.14	135	3.88	-0.97	-0.92	0.1932	-0.87	0.00	0.00
11	41.93	43.94	140	3.74	-0.57	-0.54	0.3000	-0.52	0.00	0.00
12	38.93	43.52	163	3.85	-1.34	-1.28	0.1142	-1.20	0.00	-0.20
13	38.46	43.13	186	3.94	-1.32	-1.26	0.1161	-1.19	0.00	-0.40
14	41.07	42.98	190	3.83	-0.52	-0.50	0.3114	-0.49	0.00	0.00
15	41.68	42.90	192	3.70	-0.34	-0.33	0.3735	-0.32	0.00	0.00
16	37.65	42.57	218	3.81	-1.42	-1.37	0.0957	-1.31	0.00	-0.31
17	42.30	42.55	218	3.69	-0.07	-0.07	0.4728	-0.07	0.00	0.00
18	42.79	42.57	218	3.58	0.06	0.06	0.5243	0.06	0.00	0.00
19	44.40	42.66	221	3.50	0.51	0.50	0.6882	0.49	0.00	0.00
20	49.10	42.98	260	3.70	1.84	1.79	0.9549	1.69	0.69	0.00
21	46.17	43.14	270	3.68	0.86	0.84	0.7940	0.82	0.51	0.00
22	50.73	43.48	325	3.94	2.07	2.02	0.9715	1.90	1.42	0.00
23	53.83	43.93	428	4.41	2.63	2.57	0.9911	2.37	2.79	0.00
24	53.60	44.33	517	4.74	2.19	2.15	0.9784	2.02	3.81	0.00
25	55.20	44.77	630	5.13	2.29	2.25	0.9827	2.11	4.92	0.00

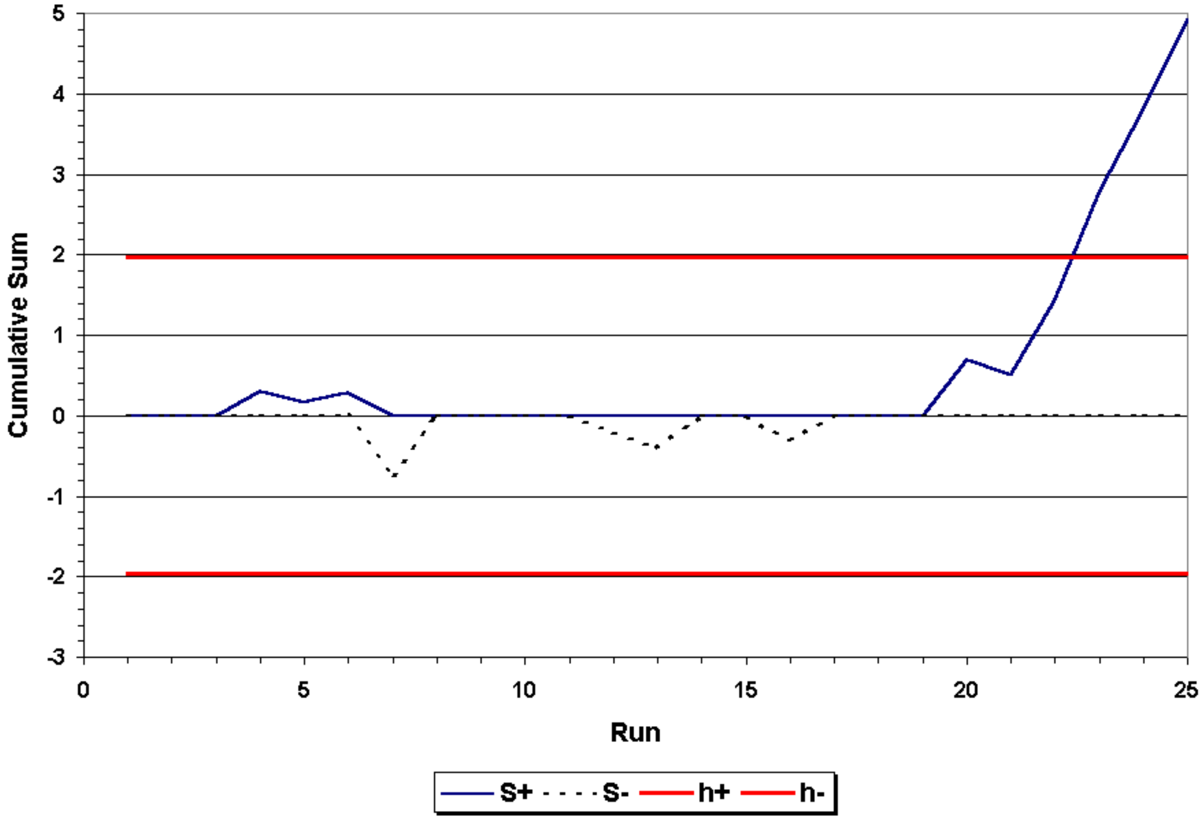


Figure C1. Example CUSUM Chart.

ATTACHMENT D. INERTIAL PROFILER CERTIFICATION

I. SCOPE

This attachment provides minimum requirements for inertial profilers to be used for quality control/quality assurance (QC/QA) of surface smoothness on TxDOT paving projects where the profile-based smoothness specification is enforced. The certification procedure covers test equipment that measures longitudinal surface profile based on an inertial reference system that is mounted on a inertial transport vehicle such as that shown in Figure D1. The minimum requirements stipulated herein are intended to address the need for accurate, precise, uniform and comparable profile measurements during construction.

II. MINIMUM REQUIREMENTS

A. Operating Parameters

The inertial profiler must be capable of providing relative elevation measurements that meet the following requirements:

1. *Reporting Interval* - the interval at which relative profile elevations are reported must be less than or equal to six inches.
2. *Cutoff Wavelength* - the algorithm for filtering the profile data must use a cutoff wavelength of 200 ft to be consistent with current TxDOT practice.

The profiler must also be able to calculate and report the IRI (in inches/mile) from the corresponding measured profile and permit the operator to:

1. Automatically trigger the start of data collection at the designated location;
2. Provide the measured profiles in electronic text files following the format prescribed by TxDOT for evaluation of profiler accuracy and repeatability as described in this attachment; and
3. Verify the height and distance measurements as described herein.

Figure D1. Illustration of a Lightweight Inertial Profiler Developed by TxDOT.

B. Equipment Certification

On an annual basis, the inertial profiler must undergo certification tests to establish that it complies with the minimum requirements for accuracy and repeatability set forth in this attachment. A profiler must also undergo certification testing after undergoing major component repairs or replacements as identified in this test method. To monitor compliance with this requirement, an item will be included in the contract documents for a given project attesting that the contractor knows and understands the requirements for profiler certification as stipulated in this test method, and that each profiler to be used on the project is current in its certification. Equipment certification involves static and dynamic tests that are described in the following.

1. Static Tests

The static tests include the laser check and distance check that are described below. These tests are run after the profiler has had time to warm-up for the duration specified by the manufacturer.

a. *Laser Check*

This test will be conducted with the profiler on a relatively flat area. Its purpose is to check the height measurements (in inches) from the laser(s) of the test vehicle using blocks of known heights. During the test, no one should lean on the profiler or cause it to move in any way. The test procedure consists of the following steps:

1. A quarter-inch base plate is positioned under the laser of the profiler and ten height measurements are taken.
2. A quarter-inch block is then positioned underneath the laser on top of the base plate and ten height measurements are again made.
3. The quarter-inch block is carefully removed from the base plate and replaced with a half-inch block. Another set of ten measurements are made.
4. Finally, the half-inch block is replaced with a one-inch block and the last set of ten measurements are taken.

The owner of the profiler to be certified shall bring his or her own base plate and gage blocks of the nominal thicknesses mentioned above. The testing agency shall measure the thicknesses of the base plate and gage blocks at three different positions on each side of the plate or block. For each piece, an average thickness shall be determined from the measurements made which shall be used in checking the lasers as described in this test. The average thickness shall also be marked on the base plate and on each gage block.

The operator of the profiler shall provide the testing agency with an ASCII or text file of the measurements. This file shall have four columns of data and ten records, indicated by the shaded cells in Table D1. The first column shall have the ten measurements made on the base plate. The second, third, and fourth columns shall have the measurements made on the quarter-inch, half-inch, and one-inch blocks, respectively.

The difference between each measurement on a gage block and the corresponding measurement on the base plate is determined to get the thickness of the gage block as measured by the laser. This calculation is done for all ten measurements on the given gage block. The absolute values of the differences between the computed thicknesses and the known average block thickness are then determined. To pass the laser check test, the average of the absolute differences must be less than or equal to 0.01 inch for each gage block.

Table D1. Format of the Data File for the Laser Check Test.

Record	Base Plate	0.25-inch Block	0.5-inch Block	1.0-inch Block
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

b. *Distance Check*

For this test, the distance measuring instrument (DMI) of the profiler shall be set to report distances in units of feet. The operator of the profiler shall drive over a delineated path for a prescribed distance of 1000 feet. Three runs shall be made. At the end of each run, the reading from the profiler's DMI is recorded. After completion of three runs, the absolute difference between the DMI reading and the known distance of the path tested shall be computed for each run. The average of the absolute differences must be less than or equal to two feet to pass the test. If the profiler's DMI does not meet this requirement, the operator of the profiler shall calibrate the DMI based on the known distance. After entering the new calibration factor, the operator shall again make three runs over the delineated path and measure the distance with the profiler's DMI on each run. The average of the absolute differences between the known distance and the DMI readings after calibration shall be computed to check if it is within the specified tolerance of two feet. If the profiler's DMI does not meet this requirement, a second calibration shall be made. If after the second calibration the profiler still fails to meet the specified tolerance, no further testing will be conducted and no certification will be given.

2. Dynamic Tests

a. *Test Sections*

Certification tests will be conducted on smooth and medium-smooth sections at a facility approved by the Texas Department of Transportation (TxDOT). Each section will be 0.1-mile in length. Ten repeat runs of the inertial profiler shall be made on the designated wheelpath of each test section in the prescribed direction of measurement. For the purpose of evaluating the profiles from the test equipment, the profile of the test wheelpath on each section shall be measured using static level methods. The test wheelpath on the smooth section shall have an IRI not exceeding 73 in/mile while the corresponding wheelpath on the medium-smooth section shall have an IRI within the range of 95 to 125 in/mile.

b. *Test Data*

Profile data from each of the ten runs made on the designated wheelpath of each test section shall be provided in an electronic file in ASCII or text format. Test data must be reported in mils and the ASCII file must follow the format used by TxDOT when collecting profile data for its Pavement Management Information System (PMIS). This will permit TxDOT to directly input profile data, collected with any inertial profiler, into its data reduction programs for PMIS. The required format of the data file is illustrated in Figure D2 and explained as follows:

(1) The first record will consist of the following items, each separated by a comma:

- (a) The first item is the identifier for the record. This shall be written as HEAD3 in the data file as illustrated in Figure D2;
- (b) Date of profile measurement in *mmddyyyy* format where *mm* is the numeric designation for the month, *dd* is the day, and *yyyy* is the year;
- (c) District where profile measurements were made in ## format. Note that ## is the two digit numeric designation for the given District (see list of Districts and counties in Figure D3);
- (d) County number in ### format;
- (e) Highway name in $$####$ format where $ represents a character descriptor;
- (f) Beginning reference marker of the measurement in ####$+##.### format;
- (g) Lane tested in $# format following PMIS convention (see lane designations in Figure D4).

(2) The second record will have the following variables, each separated by a comma:

- (a) The first item is the identifier for the record. This shall be written as CMET3 in the data file as illustrated in Figure D2;
- (b) Model designation of the inertial profiler used for testing;
- (c) The third, fourth, fifth and sixth items in the record are reserved for the use of the profile manufacturer or the contractor. Note that if these items are blanks, the comma delimiting each item must still appear in the record as shown in Figure D2;

```
HEAD3, 06241999, 17, 21, SH0047, 0413 +00.200, R1
CMET3, Profiler Model,,,,,Certification number, Certification date
Manufacturer  mil  LR  5.4882  i
Comment
Comment
-797  -869
-796  -834
-781  -824
-752  -821
-746  -824
-752  -811
-738  -790
-702  -756
-696  -738
-704  -727
-706  -730
-669  -708
-649  -705
-644  -702
-645  -668
-610  -674
-568  -635
-560  -627
-574  -620
-568  -591
-534  -588
-501  -571
-480  -549
-463  -547
-457  -493
-415  -486
-396  -454
-398  -425
-370  -398
-351  -369
-335  -353
-325  -328
-308  -305
-286  -297
-257  -274
-253  -250
-228  -238
-206  -188
-187  -202
-169  -187
-160  -157
-150  -138
-127  -111
-112  -134
-107  -111
-101  -88
-75  -75
-61  -48
-48  -54
```

Figure D2. Required Format of Profile Data File.

DISTRICT 1
(Paris)
- 60 Delta
- 75 Fannin
- 81 Franklin
- 92 Grayson
- 113 Hopkins
- 117 Hunt
- 139 Lamar
- 190 Rains
- 194 Red River

DISTRICT 2
(Fort Worth)
- 73 Erath
- 112 Hood
- 120 Jack
- 127 Johnson
- 182 Palo Pinto
- 184 Parker
- 213 Somervell
- 220 Tarrant
- 249 Wise

DISTRICT 3
(Wichita Falls)
- 5 Archer
- 12 Baylor
- 39 Clay
- 49 Cook
- 169 Montague
- 224 Throckmorton
- 243 Wichita
- 244 Wilbarger
- 252 Young

DISTRICT 4
(Amarillo)
- 6 Armstrong
- 33 Carson
- 56 Dallam
- 59 Deaf Smith
- 91 Gray
- 99 Hansford
- 104 Hartley
- 107 Hemphill
- 118 Hutchinson
- 148 Lipscomb
- 171 Moore
- 179 Ochiltree
- 180 Oldham
- 188 Potter
- 191 Randall
- 197 Roberts
- 211 Sherman

DISTRICT 5
(Lubbock)
- 9 Bailey
- 35 Castro
- 40 Cochran
- 54 Crosby
- 58 Dawson
- 78 Floyd
- 84 Gaines
- 86 Garza
- 96 Hale
- 111 Hockley
- 140 Lamb
- 152 Lubbock
- 153 Lynn
- 185 Parmer
- 219 Swisher
- 223 Terry
- 251 Yoakum

DISTRICT 6
(Odessa)
- 2 Andrews
- 52 Crane
- 69 Ector
- 151 Loving
- 156 Martin
- 165 Midland
- 186 Pecos
- 195 Reeves
- 222 Terrell
- 231 Upton
- 238 Ward
- 248 Winkler

DISTRICT 7
(San Angelo)
- 41 Coke
- 48 Concho
- 53 Crockett
- 70 Edwards
- 88 Glasscock
- 119 Irion
- 134 Kimble
- 164 Menard
- 192 Reagan
- 193 Real
- 200 Runnels
- 207 Schleicher
- 216 Sterling
- 218 Sutton
- 226 Tom Green

DISTRICT 8
(Abilene)
- 17 Borden
- 30 Callahan
- 77 Fisher
- 105 Haskell
- 115 Howard
- 128 Jones
- 132 Kent
- 168 Mitchell
- 177 Nolan
- 208 Scurry
- 209 Shackelford
- 217 Stonewall
- 221 Taylor

DISTRICT 9
(Waco)
- 14 Bell
- 18 Bosque
- 50 Coryell
- 74 Falls
- 98 Hamilton
- 110 Hill
- 147 Limestone
- 161 McLennan

DISTRICT 10
(Tyler)
- 1 Anderson
- 37 Cherokee
- 93 Gregg
- 108 Henderson
- 201 Rusk
- 212 Smith
- 234 Van Zandt
- 250 Wood

DISTRICT 11
(Lufkin)
- 3 Angelina
- 114 Houston
- 174 Nacogdoches
- 187 Polk
- 202 Sabine
- 203 San Augustine
- 204 San Jacinto
- 210 Shelby
- 228 Trinity

DISTRICT 12
(Houston)
- 20 Brazoria
- 80 Fort Bend
- 85 Galveston
- 102 Harris
- 170 Montgomery
- 237 Waller

DISTRICT 13
(Yoakum)
- 8 Austin
- 29 Calhoun
- 45 Colorado
- 62 DeWitt
- 76 Fayette
- 90 Gonzales
- 121 Jackson
- 143 Lavaca
- 158 Matagorda
- 235 Victoria
- 241 Wharton

DISTRICT 14
(Austin)
- 11 Bastrop
- 16 Blanco
- 27 Burnett
- 28 Caldwell
- 87 Gillespie
- 106 Hays
- 144 Lee
- 150 Llano
- 157 Mason
- 227 Travis
- 246 Williamson

DISTRICT 15
(San Antonio)
- 7 Atascosa
- 10 Bandera
- 15 Bexar
- 46 Comal
- 83 Frio
- 95 Guadalupe
- 131 Kendall
- 133 Kerr
- 162 McMullen
- 163 Medina
- 232 Uvalde
- 247 Wilson

DISTRICT 16
(Corpus Christi)
- 4 Aransas
- 13 Bee
- 89 Goliad
- 126 Jim Wells
- 129 Karnes
- 137 Kleberg
- 149 Live Oak
- 178 Nueces
- 196 Refugio
- 205 San Patricio

DISTRICT 17
(Bryan)
- 21 Brazos
- 26 Burleson
- 82 Freestone
- 94 Grimes
- 145 Leon
- 154 Madison
- 166 Milam
- 198 Robertson
- 236 Walker
- 239 Washington

DISTRICT 18
(Dallas)
- 43 Collin
- 57 Dallas
- 61 Denton
- 71 Ellis
- 130 Kaufman
- 175 Navarro
- 199 Rockwall

DISTRICT 19
(Atlanta)
- 19 Bowie
- 32 Camp
- 34 Cass
- 103 Harrison
- 155 Marion
- 172 Morris
- 183 Panola
- 225 Titus
- 230 Upshur

DISTRICT 20
(Beaumont)
- 36 Chambers
- 101 Hardin
- 122 Jasper
- 124 Jefferson
- 146 Liberty
- 176 Newton
- 181 Orange
- 229 Tyler

DISTRICT 21
(Pharr)
- 24 Brooks
- 31 Cameron
- 109 Hildago
- 125 Jim Hogg
- 66 Kenedy
- 214 Starr
- 245 Willacy
- 253 Zapata

DISTRICT 22
(Laredo)
- 64 Dimmit
- 67 Duval
- 136 Kinney
- 142 La Salle
- 159 Maverick
- 233 Val Verde
- 240 Webb
- 254 Zavala

DISTRICT 23
(Brownwood)
- 25 Brown
- 42 Coleman
- 47 Comanche
- 68 Eastland
- 141 Lampasas
- 160 McCulloch
- 167 Mills
- 206 San Saba
- 215 Stephens

DISTRICT 24
(El Paso)
- 22 Brewster
- 55 Culberson
- 72 El Paso
- 116 Hudspeth
- 123 Jeff Davis
- 189 Presidio

DISTRICT 25
(Childress)
- 23 Briscoe
- 38 Childress
- 44 Collingsworth
- 51 Cottle
- 63 Dickens
- 65 Donley
- 79 Foard
- 97 Hall
- 100 Hardeman
- 135 King
- 138 Knox
- 173 Motley
- 242 Wheeler

Figure D3. List of Districts and Counties in Texas.

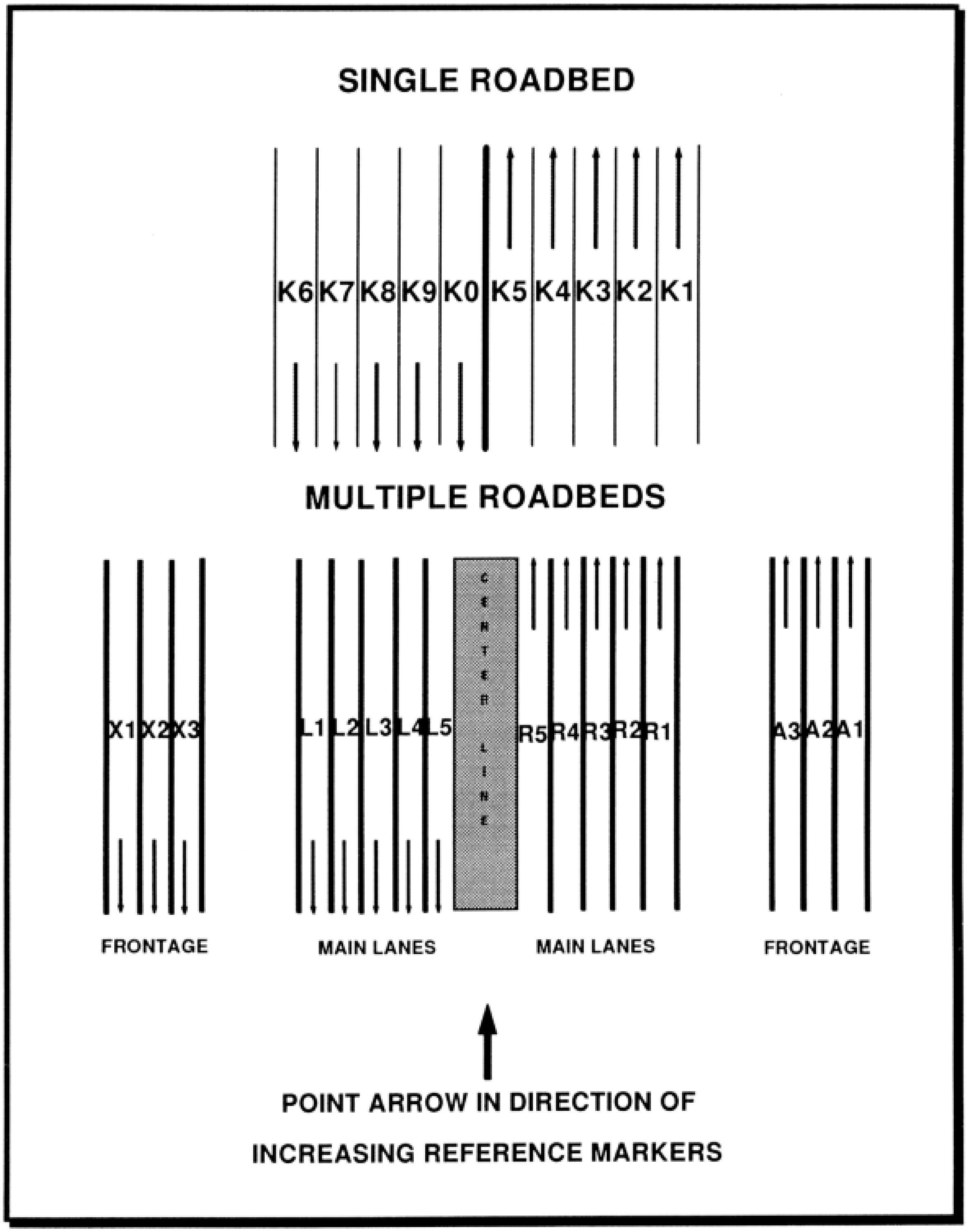


Figure D4. TxDOT PMIS Lane Designations.

(d) The seventh item in the record is the certification number for the given profiler that is issued by the testing agency upon passing the tests described herein. Prior to certification, this item may be left blank and a comma placed to delimit it in the file;
(e) The last item in the record is the certification date in *mmddyyyy* format.

(3) The third record will have the following variables, with a space separating each variable:

(a) Manufacturer of inertial profiler (alphanumeric);
(b) The unit of length used to report profile. Under the current TxDOT practice, this shall be mil (0.001 inch) as shown in Figure D2;
(c) The wheelpath measured designated as L for left, R for right, or LR for dual wheelpath profilers. Note that L and R are relative to the prescribed direction of measurement for the certification tests. For dual wheelpath profilers, the order in which the L and R appears shall correspond to the order in which the relative elevations at a given station are reported in the file. Thus, if the entry is LR, the left wheelpath elevation is reported first, followed by the right wheelpath elevation at a given station;
(d) The reporting interval (distance between successive relative elevation measurements). This interval is reported in inches for this specification;
(e) The unit of the reporting interval in item (d) above, designated as *i* for inches, or *m* for meters.

(4) The fourth and fifth records are reserved for comments that the operator may want to write into the file. If there are no comments, these records are blanks.

The first five records of the ASCII data file are thus header cards. Following the fifth header record, the relative measurements at each station are reported. For profilers that measure only one wheelpath in a given run, there shall be a column of numbers after the fifth header record consisting of the relative elevations measured at different locations or stations along the lane surveyed. There shall be as many records following the fifth header card as there are stations where elevation measurements have been collected.

For profilers with sensors on both sides for measuring two wheelpaths at the same time, profile data on the designated wheelpaths of each test section shall be collected, with one set of measurements taken using the sensors on one side of the profiler, and the second set using the sensors on the other side. For these profilers, the spacing between wheelpath sensors shall be set at the spacing of the reference wheelpaths. The testing agency will provide the wheelpath spacing to the owner of the inertial profiler prior to testing. The current spacing is 69 inches corresponding to the distance between the lasers of TxDOT's inertial profilers.

Thus, for each station where elevation measurements have been taken, there will be a record in the data file which will report the elevations for each wheelpath tested, with at least a space separating the two wheelpath elevation readings. The order in which wheelpath measurements are reported must be consistent with the wheelpath descriptor written in the third header card of the ASCII data file.

During the certification tests, the same wheelpath(s) is measured for all runs on a given test section. There will be twice more data collected and analyzed when dual-path inertial profilers are tested. To facilitate the analysis of the data, the files from the tests described herein shall be named according to the following convention:

(1) The first four characters of the file name are reserved for identifying the profiler tested. This identification will be established by the testing agency and given to the operator of the profiler on or before the day of testing.
(2) The fifth character shall be *S* for runs made on the smooth section or *M* for runs on the medium-smooth section.
(3) The sixth and seventh characters shall designate the run number (01 to 12).
(4) The eighth character shall designate the wheelpath tested. For dual-path profilers, the letter *B* shall be used to indicate that both wheelpaths were profiled in the same run. For single-path profilers, the designation for the test wheelpath will be given by the testing agency to the operator of the profiler on or before the day of testing.

The extension *PRO* shall be used for the data files to be provided by the operator of the profiler.
Test data will be analyzed as described in the following to establish the repeatability and accuracy of the test equipment.

c. *Equipment Repeatability*

To evaluate repeatability, the standard deviation of the ten repeat measurements at each reporting interval will be computed for each wheelpath surveyed. These standard deviations will be calculated for all reporting intervals. For each wheelpath, the average of the standard deviations at the different reporting intervals will be determined. Thus, for single-path inertial profilers, two averages will be determined, one for the smooth, and the other for the medium-smooth section. For dual-path profilers, four average standard deviations will be determined, two for each section. To pass the repeatability test, each average standard deviation must not exceed 35 mils.

d. *Equipment Accuracy*

The benchmark or reference profiles on the test section shall be established using static methods such as the rod and level, Dipstick and/or other suitable devices that provide unfiltered profiles. As a minimum, reference elevations shall be collected at intervals no greater than six inches. Devices that measure and integrate differential elevations, such as the Dipstick and Walking Profiler, may be used to establish the benchmark profiles. However, the measurements from these devices must be checked with the rod and level at distances along the test wheelpath that are multiples of the reporting interval for these devices. For the Dipstick, the reporting interval is 12 inches, while for the Walking

Profiler, it is 9.5 inches. Benchmark profiles obtained from the Walking Profiler shall be checked against rod and level measurements at 95-foot intervals along the test wheelpath. Dipstick measurements shall be checked against the rod and level at 100-foot intervals. Reference profile measurements shall be made on the designated wheelpath of each test section as well as on the lead-in to the section. The lead-in distance shall be at least 300 feet.

The reference profiles shall be filtered using the same filter type implemented with the profiler tested. For this purpose, the owner or manufacturer of the profiler shall provide an IBM-compatible computer program to accomplish this filtering. The testing agency shall use this program to filter the reference profiles for evaluating the accuracy of the measurements from the profiler. This program must be set up to use a 200-ft cutoff wavelength and read the reference profile from an ASCII or text file that has the format shown in Figure D2. Additionally, the program must output the filtered reference profile in an ASCII or text file according to the format given in Figure D2. The executable copy of the filter program shall be kept by the testing agency.

The test profiles will be synchronized, as necessary, so that the interval between reported elevations is the same as the interval between points in the filtered reference profiles. To evaluate accuracy, the average profile from the ten repeat runs on a given wheelpath is determined. This is done by computing the mean of the relative elevations from the ten repeat runs on a point-by-point basis, i.e., at each reporting interval. In the same manner, the average of the filtered reference profiles on the test wheelpath is also determined. For the determination of the average filtered reference profile, at least three repeat measurements of the profile shall be used. Differences between the average test profile and the average filtered reference profile are then calculated, point-by-point. The average of these differences ($:_1$), as well as the average of the absolute differences ($:_2$) are computed to establish the accuracy of the inertial profiler. The average difference is a measure of the bias in the data from a given profiler. The closer this statistic is to zero, the better the indication that a given profiler does not tend to underestimate or overestimate the profile relative to the reference used. It may be positive or negative. On the other hand, the average of the absolute differences indicates the degree of agreement between the test and reference profiles. The smaller the magnitudes of the differences between the test and reference profiles, the closer this statistic is to zero.

For single-path profilers, two sets of $:_1$ and $:_2$, are determined, one set for each test section. For dual-path profilers, four sets of these statistics are determined, two for each section. To pass the accuracy test, the average of the point-to-point differences, $:_1$, must be within ∀10 mils and the average of the absolute differences, $:_2$, must not be greater than 60 mils for all sets of statistics determined.

e. *Verification of Computed Ride Statistics*

The test equipment must be capable of computing and reporting the IRI of each wheelpath tested. The repeatability of these ride statistics shall be determined in the following manner:

(1) Ten IRI values are computed using the profiles from the ten repeat runs made on a given wheelpath.
(2) For each test wheelpath, the standard deviation of the IRIs is computed. For single-path profilers, two standard deviations are determined, one for each section. For dual-path profilers, four standard deviations are computed, two per section.
(3) To pass the repeatability test based on the computed ride statistics, each standard deviation of the IRIs determined in step (2) must not exceed 3.0 in/mile.

The average of the IRIs is also determined for each wheelpath. To evaluate the accuracy of the IRIs from the test data, the average IRI is compared against the corresponding average determined from the unfiltered reference profiles. The absolute difference between the average
IRIs from the profiler and the reference must not exceed 12 in/mile for each wheelpath tested.

III. TEST RESULTS

The results of the certification tests shall be reported by the testing agency and shall include the following information:

1. The identification of the profiler tested;
2. Operator of the profiler;
3. The name of the individual from the testing agency who conducted the test;
4. Date of test;
5. The number of paths the profiler can measure in the same run;
6. The filter type, name of the filter program and the applicable program version number used to evaluate the profiler accuracy;
7. The overall determination from the test: *Pass* or *Fail*;
8. The individual test results determined from the static tests which shall include:

    a. The average thickness determined for the base plate and for each gage block;
    b. The average of the absolute differences between the known thickness of a gage block and the thicknesses predicted from the laser of the test vehicle, reported for each gage block; and
    c. A statement of whether the DMI of the profiler passed or failed the distance check.

9. If the profiler's DMI passed the distance check, the individual test results determined from the dynamic tests shall be reported. This report shall include the following for each wheelpath tested:

   a. The average standard deviation of repeat profile measurements;
   b. The statistics, $:_1$ and $:_2$, for evaluating the accuracy of the profiles with respect to the reference;
   c. The standard deviation of the IRIs computed from the profiles;
   d. The average of the IRIs determined from the profiler test data, the average of the IRIs determined from the unfiltered reference profiles, and the absolute difference between the two averages.

   The report will also label each test result with a *Pass* or *Fail* depending on whether the given test value meets or fails to meet the prescribed criterion. The profiler must pass all tests to be certified. A decal shall be placed on the profiler as evidence of certification. This decal shall show the expiration date (month and year) of the certification.

Appendix N – Texas Ride Quality for Pavement Surfaces

1993 Specifications

SPECIAL SPECIFICATION

ITEM XXXX

RIDE QUALITY FOR PAVEMENT SURFACES

1. Description. This Item shall govern the evaluation of ride quality for pavement surfaces using either an inertial profiler or a profilograph.

2. General. The use of a profilograph will not be allowed on any TxDOT project after January 1, 2003. The finished surface of the pavement shall be smooth and true to the established line, grade and cross section shown on the plans.

   A. Transverse Profile. The transverse slope of the finished riding surface shall be tested in accordance with Surface Test Type A.

   B. Longitudinal Profile. Surface Test Type B shall apply longitudinally along the finished riding surface of all travel lanes unless Surface Test Type A is shown on the plans. Surface Test Type B shall apply longitudinally along the finished riding surface of all travel lanes except service roads, ramps or other areas excluded on the plans. For those areas where Surface Test Type B is not required, Surface Test Type A shall be used. Surface Test Type B may be required on service roads and ramps if called for on the plans. Surface Test Type A shall be used on all intermediate pavement surfacing layers unless Surface Test Type B is specified on the plans.

   When the project plans call for the existing roadway to receive an overlay of hot mixed asphalt pavement composed of at least 1.5 inches of surfacing without any level-up, milling or in-place recycling techniques, then the existing International Roughness Index (IRI) will be measured by the Engineer and made available to the Contractor prior to bid letting. Any 0.1 mile section(s) within the project limits that has an existing (before contract letting) average lane roughness exceeding 95.0 inches per mile will be excluded from any penalty pay adjustment; however, any bonus adjustment, when achieved, will be paid as specified herein. However, if the overlay thickness called for on the plans is 2.5 inches or more, then the IRI of the existing pavement will not be measured by the Engineer and the Contractor must comply with all further requirements of this specification.

   For concrete pavements, the daily average pay adjustments will be determined by subtracting 10.0 inches/mile from the actual field measured inertial profiler IRI results or, in the case of profilograph use, calculated IRI results.

3. Testing Procedures. The surface finish shall be tested in accordance with requirements below.

   A. Surface Test Type A. The surface or layer shall be tested with a 10-foot straightedge at locations selected by the Engineer.
   B. Surface Test Type B. The surface or layer shall be tested using either an inertial profiler or a profilograph as specified below. To ensure that the equipment selected for measuring smoothness is maintained in proper operating condition during the course of the paving project, the Contractor shall establish a 0.1-mile control section as approved by the Engineer. The Contractor shall use this section to establish and maintain a control chart for this equipment in accordance with Test Method Tex-1001-S. Prior to measuring surface smoothness for acceptance of the day's production, the Contractor shall perform vertical and horizontal calibrations following the manufacturer's guidelines for the specific equipment. After these calibrations, the Contractor shall propel the test equipment over the control section and determine the IRI. The resulting IRI shall be used to verify that the equipment is within the tolerance limits as established by the control chart. If the equipment is out of tolerance based on the control chart, the Contractor shall determine the cause for the discrepancy and adjust or repair the equipment as needed. A log shall be maintained with the equipment to provide a verification of calibration history. Failure to maintain the log as specified may result in withholding of ride pay adjustments until the Engineer has obtained ride data from a TxDOT owned and operated inertial profiler. The profiler or profilograph shall not be used for quality assurance testing until the Contractor can show, to the satisfaction of the Engineer, that the equipment is properly calibrated.

      (1) When an inertial profiler is used, it shall meet the requirements of Test Method Tex-1001-S, shown to be in good working order, and properly maintained. The equipment shall be calibrated in accordance with the manufacturer's specification and must be certified for use by the Texas Transportation Institute in accordance with Attachment E of Test Method Tex-1001-S. This certification shall be performed at least on an annual basis at the TxDOT Ride and Rut Calibration Facility in College Station, Texas. Each certified inertial profiler shall have a current certification sticker attached in a conspicuous location. The cost of the certification process shall be paid by the owner of the inertial profiler. If repairs to or replacement of major components, as detailed in Test Method Tex-1001-S, are made to an inertial profiler within the one-year certification period, the owner must obtain a re-certification at the owner's expense. A new certification sticker will be attached to the inertial profiler and will extend over a one-year period from the date of the re-certification or at such time as more repairs become necessary.

      The Contractor shall propel the inertial profiler under the direction of the Engineer. The results of the inertial profiler test shall be evaluated by the Contractor's Level IB Certified Specialist and verified by the Engineer's

Level IB Certified Specialist in accordance with Test Method Tex-1001-S. Paving operations for subsequent days shall not continue until the Contractor has provided the Engineer with previous days' inertial profiler test results except as specifically provided under Subarticle 3. E.

An inertial profiler shall not be used in a profilograph simulation mode for quality assurance to determine pay adjustments; however, it may be used by the Contractor in any mode for quality control.

(2) When a profilograph is used, it shall meet the requirements of Test Method Tex-1001-S, shown to be in good working order, and properly maintained. The equipment shall be calibrated by the Contractor and calibration verified by the Engineer in accordance with Test Method Tex-1001-S prior to its use on the project. The Contractor shall propel the profilograph under the direction of the Engineer. The results of the profilograph test shall be evaluated by the Contractor's Level IB Certified Specialist and verified by the Engineer's Level IB Certified Specialist in accordance with Test Method Tex-1001-S. Paving operations for subsequent days shall not continue until the Contractor has provided the Engineer with the previous days' profilograph test results except as specifically provide under Subarticle 3. E.

A properly calibrated, automated means of reducing profilograph data shall be required as stipulated in Tex-1001-S.

C. Scope. Testing will be limited to those pavement surfaces having a construction length of 0.1 mile or more. All horizontal curves shall be profiled; however, no penalty will be assessed for sections of horizontal curves with a centerline radius of less than 1000 feet including the super elevation to such curves. Any bonus determined from the testing will be paid.

Pavements within 25 feet of a transverse joint which separates the pavement from an existing pavement not placed by this project, the beginning of a bridge structure or an approach slab that is not overlaid under this project will not be subjected to this test. Also, the first 25 feet from the end of a bridge structure or approach slab that is not overlaid under this project will not be subjected to this test. When an inertial profiler is used, this distance will be part of the 200-foot lead-in which will be used to get up to test speed and settle the electronics of the equipment prior to obtaining recorded data.

In addition, when the Engineer allows or directs traffic to cross a newly placed mat prior to final rolling, the area being crossed and an additional distance of 100 feet on either side shall be excluded from testing when requested by the Contractor. These areas may include intersecting roadways, driveways or other access points. These areas shall be evaluated using the 10-foot straightedge as outlined herein.

However, when the surfacing materials being placed under this contract are placed over the bridge structure and/or approach slab, these areas will be subject to the same criteria as the rest of the pavement surfacing project except that no penalty will be assessed for the sections that include the bridge or approach slabs. Any bonus determined from the testing will be paid.

D. Pavement Profiles. Pavement profiles shall be obtained on a daily basis for each 0.1-mile of surfacing placed. The pavement profile shall commence a minimum of 25 feet into the previously measured placement and shall be taken along both of the approximate wheel paths of each travel lane. The profile location will normally lie three feet from and parallel to the approximate location of the pavement lane lines. The IRI used for evaluating each 0.1-mile section of each travel lane to determine its payment bonus or deduction shall be the average of these two profiles. The inertial profiler or profilograph shall be used to identify the limits of an out-of-tolerance surface variation. Measurements shall be performed in the direction of traffic unless otherwise approved by the Engineer. The measurements from each wheelpath in a travel lane shall start and stop at the same longitudinal locations.

Short sections less than 0.1-mile at the end of a day's operation shall be measured in conjunction with the next day's operation except at the end of the project or where bridge or approach slabs are encountered. For these short sections, the IRI shall be calculated on a pro-rata basis as described in Test Method Tex-1001-S if greater than 50 feet. Short segments less than 50 feet in length shall be evaluated using the 10-foot straight edge "Surface Test Type A" and will not be included in the bonus and penalty payment schedule.

E. Initial Paving Operation. During the initial day of paving operations, the pavement surface shall be tested with the inertial profiler or profilograph as soon as possible without damaging the pavement surface. The purpose of this initial testing is to aid the Contractor and the Engineer in evaluating the paving methods and equipment. When the paving methods and paving equipment do not result in a negative pay adjustment calculation, the Contractor may proceed with the paving operation.

When this initial paving operation results in a negative pay adjustment calculation, the Contractor shall make correction in the paving operations before proceeding. There will be no pay adjustment for the initial day of paving unless the Contractor elects to waive the requirements and begin acceptance testing in accordance with Subarticle 4 and pay adjustments in accordance with Subarticle 5. This notification shall be made in writing to the Engineer prior to the first day of paving.

F. Daily Average Pay Adjustment. The daily average pay adjustment is obtained by averaging the pay adjustments of all 0.1-mile sections of pavement placed during each day's paving. The daily average pay adjustment is not used to calculate actual pay, but only as a guideline for corrective action as follows.

When the daily average pay adjustments for any day result in a pay deduction, the Contractor shall evaluate the paving operation and take corrective action. When two consecutive daily average pay adjustments result in a pay deduction, operation shall cease until test results, or other information indicate to the satisfaction of the Engineer that the next material to be placed will not result in a daily average pay deduction.

G. Referee Testing. At any time during the course of the paving operation, the Engineer may perform independent ride quality testing using a certified TxDOT inertial profiler. If the TxDOT results produce an IRI value of the two wheel paths averaged over a 0.1 mile section of more than +/- 12.0 inches per mile from that obtained using the Contractor's equipment, then the Engineer and the Contractor shall attempt to resolve the differences. If the differences cannot be resolved, then the Engineer may request referee testing. All referee testing will be conducted by the Design Division and will be final.

If the Contractor is using an inertial profiler, then TxDOT will use an independent and certified inertial profiler for the referee testing. Comparison tests shall be performed on the Contractor's previously established control section. Prior to testing, the control section shall be cleaned of debris and the wheel paths shall be marked. The Contractor shall make ten measurements of the profiles on the control section using the Contractor's equipment. The Contractor will provide all profile measurements to the Engineer in electronic data files with the format specified in Attachment A to Test Method Tex-1001-S. Likewise, ten measurements will be made using the Design Division's referee profiler on the same wheelpaths. All profile measurements will be made in the same direction.

The IRI will be calculated for each wheelpath profile determined from a given run. A statistical analysis will be made in accordance with Test Method Tex-1001-S. This statistical test will be made at a confidence level of 95 percent. The analysis of the data for this comparative testing will be made using TxDOT's computer program for referee testing developed for this test method. If the analysis shows a significant difference between the Contractor's profiler and the referee profiler, the Contractor's profiler will be reported as non-compliant and its certification will be revoked. The Design Division referee profiler will then be used to establish pay adjustment factors for all sections in question. The Contractor shall be required to have the non-compliant profiler re-certified or otherwise obtain a profiler with a valid certification. While a replacement profiler is being obtained, the Contractor may request in writing that the project continue for a period of not more than five working days and be tested after a replacement profiler has been obtained. Any bonus or penalties accrued during the five day period shall be assessed upon proper measurement with a certified profiler. The Contractor will not be allowed to replace an inertial profiler with a profilograph.

If the statistical analysis shows the Contractor's inertial profiler to be within tolerance, then the TxDOT Regional profiler will be taken out of service until it has been re-certified. The Contractor's results will be used to establish pay factor adjustments.

If the Contractor is using a profilograph, the control section tests described in Test Method Tex-1001-S shall be used to determine if the Contractor's profilograph is defective. The Contractor shall replace or repair any defective profilograph. While a replacement profilograph is being obtained, the Contractor may request in writing that the project continue for a period of not more than five working days and be tested after a replacement profilograph has been obtained. The Contractor may replace a profilograph with a certified inertial profiler.

4. Pavement Evaluation and Corrections

A. Surface Test Type A. The variation of the surface from the testing edge of the straightedge shall not exceed 1/8 inch between any two (2) contacts, when measured longitudinally or transversely. All irregularities exceeding the specified tolerance shall be corrected as approved by the Engineer at the Contractor's expense. Following correction, the area shall be retested to verify compliance with this Item.

B. Surface Test Type B. After the pavement surface has been tested and evaluated for overall smoothness, it shall then be evaluated for localized roughness or surface deviations (bumps or scallops) as follows:

(1) Profilograph. When using the profilograph, surface deviations shall be evaluated using a "bump template" and any deviation in excess of 0.30 inches in 25 feet shall be considered "out of tolerance". These "out of tolerance" sections shall either be assessed a penalty of $500.00 per occurrence or corrected as directed by the Engineer. The Engineer will determine whether to require corrective action or to assess the penalty.

(2) Inertial Profiler. When using the inertial profiler, surface deviations shall be determined using a 10 foot straightedge and any deviation between any two contacts that exceed 1/8 inch in 10 feet shall be considered "out of tolerance". These "out of tolerance" sections shall be assessed a penalty of $500.00 per occurrence or corrected as directed by the Engineer. The Engineer will determine whether to require corrective action or to assess the penalty.

Any 0.1-mile section having an average IRI of over 97.0 inches/mile shall be corrected to produce an IRI of 62.9 inches/mile or less. On those 0.1-mile sections where corrections are required, the corrected pavement section shall be reprofiled to verify that corrections have produced the required improvements. When corrective action is taken to improve the IRI and the surface deviations noted above are also eliminated, then any associated penalty will be waived and no bonus will be paid (see Subarticle 5.B. below.) The Contractor shall demonstrate that any proposed corrective work will produce results satisfactory to the Engineer. All corrective work shall be at the Contractor's expense.

5. Pay Adjustment. The pay adjustment for ride quality will be determined as follows:

   A. Surface Test Type A. No pay adjustment will be made when Surface Test Type A is used except when determining bumps or scallops under Surface Test Type B.

   B. Surface Test Type B. Pay adjustment will be made in accordance with Table 1 and with Subarticle 4.B. above. No bonus will be paid for pavement sections that were originally constructed under this item with a pay deduction excluding pay deductions for bumps as identified under Subarticle 4.B. There will be no pay adjustments for the sections where the Contractor took successful corrective action. When a profilograph is used, the "Zero" blanking band PI in inches per mile shall be converted to IRI in inches per mile using the following equation:

$$IRI = \frac{4.445 \times PI}{1 + (0.02073 \times PI)}$$

6. Measurement and Payment. The work performed, materials furnished and all labor, tools, equipment and incidentals necessary to complete the work under this Item will not be measured or paid for directly, but will be considered subsidiary to the various bid items of the contract. The pay adjustment as shown in the appropriate schedule and in Subarticle 4.B. above will be paid or deducted separately.

Appendix O – ASTM E 950-98: Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference

Designation: E 950 – 98

AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference[1]

This standard is issued under the fixed designation E 950; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the measurement and recording of the profile of vehicular-traveled surfaces with an accelerometer established inertial reference on a profile-measuring vehicle.

1.2 The test method uses measurement of the distance between an inertial plane of reference and the traveled surface along with the acceleration of the inertial platform to detect changes in elevation of the surface along the length being traversed by the instrumented vehicle. In order to meet a particular class, the transducers must meet accuracy requirements and the calculated profile must meet the specifications of that class.

1.3 The values measured represent a filtered profile measured from a moving plane of reference using the equipment and procedures stated herein. The profile measurements obtained should agree with actual elevation measurements that are subjected to the same filtering. Selection of proper filtering allows the user to obtain suitable wavelength information for the intended data processing.

1.4 Either metric or inch-pound units may be used, but must be used consistently and not mixed.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary information is given in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*

E 178 Practice for Dealing with Outlying Observations[2]

E 867 Terminology Relating to Traveled Surface Characteristics[3]

E 1166 Guide for Network Level Pavement Management[3]

E 1364 Test Method for Measuring Road Roughness by Static Level Method[3]

F 457 Test Method for Speed and Distance Calibration of a Fifth Wheel Equipped with Either Analog or Digital Instrumentation[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *aliasing—in the context of this practice,*—the spectrum of a digitized data record exists over the range of frequencies from zero to one half the sampling frequency. If the spectrum of the original signal extends beyond one half the sampling frequency, then those components of the signal at frequencies higher than one half the sampling frequency will, when digitized, be folded back into the spectrum of the digitized signal. The excessively high frequency components will thus be "aliased" into low frequency components.

3.1.2 *anti-aliasing filter*—a low-pass analog filter applied to the original analog profile signal to suppress those components of the signal at frequencies higher than one half the intended digital sampling frequency.

3.1.3 *frequency domain filtering*—a filtering operation performed by first calculating the the spectrum of the profile record and then multiplying the spectral components by the frequency response transfer function of the filter.

3.1.4 *profile record*—a data record of the surface elevation, slope, or acceleration, of arbitrary length.

3.1.5 *profile segment*—that part of a profile record for which the profile index will be calculated.

3.1.6 *spatial domain filtering*—a filtering operation performed directly on the profile record

4. Summary of Test Method

4.1 The test apparatus consists of a vehicle equipped with the necessary transducers, computing, and recording equipment to measure and record elevation profile of the traveled surface **(1)**.[5]

4.2 The sampling rate is selected and depends on the anticipated roadway conditions and data requirements for the intended data processing.

[1] This test method is under the jurisdiction of ASTM Committee E-17 on Vehicle-Pavement Systems and is the direct responsibility of Subcommittee E17.31 on Methods for Measuring Profile and Roughness.

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[2] *Annual Book of ASTM Standards*, Vol 14.02.

[3] *Annual Book of ASTM Standards*, Vol 04.03.

[4] *Annual Book of ASTM Standards*, Vol 09.02.

[5] The boldface numbers in parentheses refer to the list of references at the end of this standard.

4.3 The test apparatus is driven in the wheel tracks or in the correct lateral location over the section of traveled surface to be profiled. Transducers measure vertical acceleration of the vehicle and the vertical distance between the accelerometer and the traveled surface and the longitudinal distance. These transducer signals are combined by a computer to produce the longitudinal profile of the traveled surface.

5. Significance and Use

5.1 The measurement of vehicular traveled surfaces using an instrumented vehicle with an inertial plane of reference provides a satisfactory method for acquiring traveled surface profile data (1).

5.2 The profile data can be processed to produce, by simulation, the outputs of other devices. This can be done on line in real time or can be computed as a post process. Some of the devices that can be simulated include road meters (2), various straightedge devices (3), profilographs, (4), as well as pavers and grinders. Comparisons of various equipment and their profile computer programs are given in reference (5, 6).

5.3 The raw data or the profile data can also be recorded for data processing at a later time and for analysis by more complex data processing procedures.

6. Apparatus

6.1 The test apparatus consists of a vehicle equipped with transducers and profile computing and recording equipment. The transducers are used to measure vertical acceleration, displacement, and the distance traveled. The computer is used to process the transducer outputs to produce the computed profile of the traveled surface. The test apparatus must have transducer capability for one or more tracks and a mass storage device for long term storage of the data. If two wheel tracks are measured, the displacement transducers shall be mounted 1.5 to 1.8 m (58 to 71 in.) apart so that they measure in the two wheel tracks of the traveled surface. A set of gage blocks must be included to calibrate and validate static transducer operation. Other supporting apparatus can include a driver speed display and a graphical display of the profile or data. Some form of data display is recommended to ensure correct data is being collected.

6.2 *Vehicle Requirements*—The vehicle is the platform for the mounting of the profile-measuring equipment. The vehicle shall be large enough to accommodate all the required equipment without major structural modifications. The engine, steering mechanisms, and suspension components shall be adequate to allow smooth maintenance of speed and direction of travel. The environment of the interior of the vehicle shall be maintained within tolerable limits of the instrumentation and operators.

6.3 *Transducers*:

6.3.1 *Accelerometer*—The accelerometer measures the acceleration used to establish the inertial reference. A high-quality accelerometer shall be used that meets the class requirements of the profiling device. The accelerometer shall be mounted on the measuring vehicle with the accelerometer's sensitive axis perpendicular to the traveled surface. The accelerometer range shall be large enough to accommodate the levels of acceleration expected from the bounce motions of the measuring vehicle (typically ± 1 g). The accelerometer shall be biased to account for the 1-g acceleration of gravity. The accelerometer or external circuitry shall contain a self-calibration external voltage source which, on command, causes the output of the acceleration signal level to change a predetermined value. The accelerometer shall have a minimum resolution to allow profile calculation and accuracy and bias to meet the class requirements as given in this standard.

6.3.2 *Displacement Measurement*—A displacement transducer measures the distance between the accelerometer and the traveled surface. The transducer shall be mounted on the vehicle with its measuring axis perpendicular to the traveled surface and in line with the sensitive axis of the accelerometer. The displacement transducer shall measure the vertical distance to the traveled surface continuously, or sample at intervals not greater than that needed to allow calculated profile as given in Table 1. The vertical resolution is that necessary to meet the class given in Table 2.

6.3.3 *Distance Measurement*—The distance transducer may be of the type that produces a series of pulses, the intervals of which represent a distance along the traveled surface to a resolution needed to satisfy Table 1. The pulses are used to measure speed and can be used to convert from a function of time to a function of distance traveled. Any distance transducer that produces analog or digital signals with sufficient accuracy may be used. The accuracy of the distance measurement is established by calibration (see 9.2.3).

6.3.4 *Location Markers*—Use of a section start, intermediate feature location(s), and section end shall be identified by location marks that can be accurately detected by an automatic means, such as magnetic detection, photocells detection of reflective tape or similar means.

6.4 *Profile Computation*—A computer shall be used to process acceleration, and distance transducer outputs to produce measured traveled surface profile. There are two basic methods of computing measured traveled surface profile:

6.4.1 *Spatial Based*—In the spatial based method, the transducer outputs are acquired and profile data points are computed as a function of the distance traveled. In the spatial-based method, the computation of measured road profile is independent of the vehicle measuring speed.

6.4.2 *Time-Based*—In the time-based system, the transducer outputs are acquired and profile data points are computed as a function of a fixed-time interval. In the time-based method, the computation of measured road profile is not independent of the vehicle measuring speed.

6.4.3 Filtering that permits the computation of measured elevation profile with no attenuation or amplification of road profile wave lengths at least 60 m (200 ft) long at test speeds of 25 to 95 km/h (15 to 60 mph) shall be provided. The computer and system shall not add noise in excess of 10 % of the displacement measuring transducer resolutions given in Table 2.

TABLE 1 Longitudinal Sampling

Class 1	less than or equal to 25 mm (1 in.)
Class 2	greater than 25 mm (1 in.) to 150 mm (6 in.)
Class 3	greater than 150 mm (6 in.) to 300 mm (12 in.)
Class 4	greater than 300 mm (12 in.)

TABLE 2 Vertical Measurement Resolution

Class 1	less than or equal to 0.1 mm (0.005 in.)
Class 2	greater than 0.1 mm (0.005 in.) to 0.2 mm (0.010 in.)
Class 3	greater than 0.2 mm (0.010 in.) to 0.5 mm (0.020 in.)
Class 4	greater than 0.5 mm (0.020 in.)

6.4.4 As part of the profile computation equipment, a computer terminal shall be provided that will allow the operator to perform system calibration, select system parameters, and monitor system outputs.

6.5 *Driver Speed Display*:

6.5.1 The vehicle speed shall be displayed conveniently for the driver to assist in maintaining the desired measuring speed on systems requiring constant speed during measurement. Some systems, especially in the case of spatial based systems, are independent of speed and the speedometer is sufficient.

6.5.2 The displayed vehicle speed, when required, may be computed by the profile computer from the distance pulses. Other means of measuring vehicle speed are acceptable.

6.6 *Display*—A display should be used that allows visual monitoring of the systems outputs. The display should allow profile amplitudes to be displayed as a function of time or distance traveled. Amplitude and distance scaling shall be controlled by the operator through the profile computer terminal.

6.7 *Storage Device*—A device shall be provided for the recording and long term storage of data or computed profile, or both. The device shall have play back ability for additional on-board processing or for later processing. Profile data for recording shall be scaled by the computer to maintain storage resolution of the computed profile and to accommodate the full range of amplitudes encountered during normal profile measuring operation. Signal to noise (S/N) ratio shall be 10 or better.

6.8 *Event Marker*—The operator shall be provided the means to event mark location data as part of the data records. The system may use a transducer (optionally) to automatically sense and automatically record location markers that have been placed on the traveled surface.

7. Safety Precautions

7.1 The test vehicle, as well as all attachments to it, shall comply with all applicable state and federal laws. Necessary precautions imposed by laws and regulations, as well as vehicle manufacturers, shall be taken to ensure safety of operating personnel and other traffic.

8. Digital Profile Recording

8.1 The computed profile shall be recorded at adequate intervals for accurate representation of the traveled surface for the intended use of the data. Also, antialiasing filters are required when the folding frequency (½ of sampling frequency) is close to the upper frequency of interest (see Terminology E 867). Identical antialiasing filtering must be applied to both the accelerometer signal and to the displacement measurement signal before computing profiles. The upper filter frequency depends upon the intended use of the profile.

8.2 Where two or more paths of traveled surface are measured, the recorded profile data for the paths shall be at the same longitudinal location. This requirement is not necessary if the analysis to be used is independent of the wheel tracks (for example, only quarter car analysis used).

9. Calibration Procedures

9.1 Due to the level of performance required of the class of traveled surface profile measuring apparatus, it is important that the system and its components be calibrated periodically as recommended by the manufacturer.

NOTE 1—Due to the complexity of the calibration, it is recommended that the calibration procedure be automated to reduce or eliminate operator involvement and decision making.

9.2 *Transducers*:

9.2.1 *Acceleration Transducer*—The acceleration transducer shall have an internal or external calibration feature. A measure of the accelerometer error shall then be displayed for the operator's acceptance. As an alternative, the acceleration transducer may be calibrated separately in the laboratory. In either case, an error larger than that allowed for the class shall not be accepted.

9.2.2 *Displacement Transducer*—The displacement transducer shall be statically calibrated by introducing an accurately measured step of displacement. The displacement step shall be at least 25 mm (1.0 in.) and accurate within class requirement. A measure of the displacement transducer error shall be displayed for the operator's acceptance or adjustment.

9.2.3 *Distance Transducer*—The distance transducer shall be calibrated by measuring a predetermined distance on a straight section in a similar manner as given in Test Method F 457. The measured distance shall be long enough to determine any significant difference between the measured distance and the predetermined actual distance. A measure of the distance transducer error shall be displayed for the operator's acceptance or adjustment. An error larger than 0.1 % of the actual distance shall not be accepted. The transducer shall be calibrated at the measuring speed(s) to be used.

10. Procedures

10.1 *General*:

10.1.1 *System Power*—Turn on electronic equipment prior to testing to allow electronic components to stabilize (see manufacturer's operating manual).

10.1.2 *System Parameters*—If required, select the system parameters that define the wavelength content of the surface profile to be measured (see manufacturer's operating manual).

10.1.3 *Calibration Checks*—Perform calibration checks at the beginning of a day of operation and at any other time the operator may suspect changes of system performance since the last calibration. Also, calibration checks should be made at the end of each day or prior to departing a region to ensure collected data is valid.

10.1.3.1 *System*—Check the calibration by using the simple procedure of bouncing the vehicle, while it is stationary, on a flat surface. This checks the major portion of the system. In this mode of operation, the surface profile is unchanging and the system output should be less than 1 % of the vehicle bounce amplitude. A measure of the traveled surface profile measuring system error shall be displayed for the operator's acceptance.

10.2 *Measuring Speed*:

10.2.1 Better quality profile calculations are generally obtained at higher measuring speeds because of the filters used. Higher measuring speeds may, however, be limited by the ability of the apparatus to measure an extremely rough surface at high speed. Measuring speed might have to be reduced for sampling of shorter intervals (7).

10.2.2 Avoid measuring speeds below 25 km/h (15 mph) since the quality of the long wavelength content of the measured profile will be affected or a much higher resolution accelerometer must be used. Measuring speeds as low as 2 m/s (5 mph) may be used where higher speeds are not practical and long wavelength content is not important; such as, on very rough roads, railroad crossings, or other special conditions.

10.2.3 Avoid sudden speed changes to minimize unwanted input to the acceleration transducer and transients to the filters.

10.3 *Test Sections*—In preparation for measuring short test sections of a traveled surface, the operator should become acquainted with the test section to be measured including the beginning, end, and any other features that should be identified within the test section. If identifying features within the test section are to be sensed automatically, the operator shall place the proper marker on the traveled surface at the locations to be identified. It is very important that the wheel tracks be identified on the roadway so that the measurements are made in the wheel tracks or in the paths that are to be measured.

10.4 *Data Acquisition*:

10.4.1 Enter information about the test section and conditions of the test (see Section 12).

10.4.2 At least 150 m (500 ft) (or at manufacturer's specified lead-in) prior to the beginning of the test section, bring the apparatus to the desired speed.

10.4.3 Prior to reaching the test section, at least 150 m (500 ft) or as needed because of the long wavelength filter, switch the system to the test mode.

10.4.4 At the start of the test section, identify its beginning as part of the recorded data. This can be done automatically or manually with an event marker.

10.4.5 Measure the surface profile within a traveled lane as close as possible to the track established by normal traffic. If a single track is measured, it should be in the center of the wheel track of the normal traffic track for that side or in the center of the path to be measured. If more than one path of the traveled surface is measured, then one track should be in the center of the normal traffic track (left or right, but should be the same each time the test section is measured). Note that if the distance between sensors is not that of the actual wheel tracks, then only one measurement is actually centered in a wheel track and should normally be the right track.

10.4.6 Observe and check that the data is reasonable as it is recorded. If profile data is collected for multiple wheel tracks, traces for the right and left wheel tracks should be very similar except for short wavelengths.

10.4.7 Identify, as part of the recorded data, other physical features or known reference points within the test section that will assist in relating the calculated profile to actual traveled surface profile.

10.4.8 Identify the end of the test section.

10.5 *Data Evaluation for Correctness*:

10.5.1 If there is a question about the performance of the test apparatus for the test run, make an immediate check by measuring the test section again. The calculated profile or a point by point basis for the two runs should be within that specified by the class the apparatus is to meet.

10.5.2 Occasionally, evaluate the profile or raw data recorded on the storage device by playing the recorded data back to the recorder or display. The calculated profile or raw data played back to the display should be identical to the data recorded on the display when it is first calculated. Any difference between the profiles indicates an equipment problem with the storage device. A printing recorder is especially helpful here.

11. Faulty Tests

11.1 Any observable differences between the measured profiles of the left and right wheel tracks (see 10.4.6) that cannot be attributed to actual differences in the roadway mandate a repeat measurement. Any observable differences between the two identical runs, in accordance with Practice E 178, other than differences due to differences in the paths that were measured, indicate an equipment problem and invalidate the tests.

12. Report

12.1 The field report for each test section shall contain data on the following items:

12.1.1 Date and time of day,

12.1.2 Operator, driver, and vehicle identification,

12.1.3 Weather conditions; principally temperature, cloud cover, and wind,

12.1.4 Location and description of test section,

12.1.5 Surface description; type of pavement and condition,

12.1.6 Run number,

12.1.7 Measuring speed,

12.1.8 Direction measured,

12.1.9 Lane measured, transverse position,

12.1.10 Profile data, and

12.1.11 Other system specific measurement options, for example, filter wavelength data interval, and resolution.

13. Precision and Bias

13.1 The accuracy of pavement profile measuring equipment can be defined by a statement on the precision and bias of the measuring equipment.

13.2 *Precision*—Precision in the measurement of pavement profile elevations is related to the closeness of agreement between repeat measurements of the same pavement profile.

13.2.1 Precision in the measurement of pavement profile is considered to be a specified combination of the repeatability standard deviation of observed values at specified locations along the measured profile.

13.2.2 The repeatability standard deviation of multiple observed values at one specified location along the measured pavement profile is expressed as a standard deviation of the multiple observed values about the computed mean value for that location.

13.2.3 The precision of a pavement profile measuring system is expressed as the mean of multiple repeatability standard deviations (SD) of the observed values at the multiple specified locations along the measured pavement profile.

13.2.4 For comparable statements of precision, the length of the measured pavement profile, the number of specified locations along the measured pavement profile, and the number of observed values at each specified location shall be maintained.

13.2.4.1 The length of the measured pavement profile to be used in the development of the precision statement shall be 320 m (1056 ft).

13.2.4.2 The number of specified locations along the measured pavement profile shall be one thousand fifty seven at 0.30 m (1.00 ft) intervals.

13.2.4.3 At least ten repeat pavement profile measurements shall be used in the development of the required precision statement.

13.2.4.4 In the development of the precision statement for the pavement profile measuring equipment, the independent variables that affect the pavement profile measuring process shall be tightly controlled.

13.2.4.5 The variation in the measurement of longitudinal profile can be minimized by selecting a pavement test section with minimal variation in the transverse pavement profile.

13.2.4.6 The variation in the measurement of longitudinal profile due to variations in transverse pavement profile can be minimized by following as closely as possible the same path during the required repeat profile measurements.

13.2.4.7 To ensure that the repeat pavement profile measurements are made at the same specified locations along the measured pavement profile, the longitudinal location of the pavement profile measurement shall be tightly controlled, for example, automatic location marks.

13.2.5 The precision requirements for equipment for the measurement of pavement profile by equipment classification shall not exceed the precision listed below.

Equipment Classification	Precision (1 SD)
1	0.38 mm (0.015 in.)
2	0.76 mm (0.030 in.)
3	2.50 mm (0.100 in.)

13.3 *Bias*—Bias in the measurement of pavement profile is related to the consistent or systematic difference between the mean value of repeat pavement profile measurements at specified locations along the measured pavement profile and an accepted reference value for those specified locations.

13.3.1 Bias in the measurement of an individual profile data point at one specified location is the computed mean value for that specified location minus the accepted reference value for that specified location.

13.3.2 An accepted reference value for a specified location along the measured pavement profile shall be derived from an accepted reference pavement profile measuring method (for example, rod and level, Test Method E 1364, etc.).

13.3.2.1 To provide the maximum confidence in the accepted reference value, it would be highly desirable to repeat the reference profile measurements enough times to determine a valid mean value and standard deviation about that mean value for the measurements made at each specified location along the measured pavement profile.

13.3.3 An accepted reference value shall be derived from the reference pavement profile measurements using the identical processing (linear filtering, etc.) as the pavement profile measuring equipment being evaluated as long as the original amplitude and phase relationship of the reference pavement profile measurements are not affected over the specified wave length range of interest.

13.3.3.1 For comparable statements of bias, the original amplitude and phase relationship of the reference pavement profile measurements shall be unaffected for pavement profile wave lengths up to 100 m (300 ft).

13.3.4 Bias in the measurement of pavement profile is considered to be a specified combination of the biases of observed values at specified locations along the measured pavement profile.

13.3.5 The bias in the measurement of longitudinal profile shall be the summation of the absolute value of the individual biases at the multiple specified locations along the longitudianl profile measurement divided by the number of specified locations.

13.3.6 For comparable statements of bias, the length of the measured pavement profile, and the number of specified locations along the measured pavement profile shall be maintained.

13.3.6.1 The length of measured pavement profile to be used in the development of the bias statement shall be 350 m (1056 ft).

13.3.6.2 The number of specified locations along the measured pavement profile shall be one thousand fifty seven at 0.3 m (1.00 ft) intervals.

13.3.7 The bias requirements for equipment for the measurement of pavement profile by equipment classification shall not exceed the biases listed below.

Equipment Classification	Bias
1	1.25 mm (0.050 in.)
2	2.50 mm (0.100 in.)
3	6.25 mm (0.250 in.)

14. Keywords

14.1 longitudinal profile; profiling device; profilometer

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